VIRGINIA DEPARTMENT OF ENVIRONMENTAL QUALITY

AMBIENT GROUNDWATER QUALITY MONITORING STRATEGY

Final - November 2013

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Problem

In many areas of Virginia, quality of life and economy depend on the availability and quality of groundwater resources drawn from wells and springs. It has been estimated that over 80% of Virginians are dependent on groundwater to meet daily needs (Water Systems Council, 2012). On average, over 200 million gallons of daily groundwater use is reported from Virginia's Industrial, Commercial, Agricultural, Mining, Public Water Supply, and Irrigation sectors. In a state with such a high dependence on groundwater resources, an improved understanding of the availability and quality of its groundwater systems is essential.

Knowledge of the distribution, quality, and use of Virginia's groundwater resources is necessary for making proper water resource management decisions, minimizing threats to human health, and for the development of Virginia's economy. Hem (1992) states, "The chemical composition of natural water is derived from many different sources of solutes, including gases and aerosols from the atmosphere, weathering and erosion of rocks and soil, solution or precipitation reactions occurring below the land surface, and cultural affects resulting from human activities". A limited amount of water quality data shows the chemical composition of groundwater varies greatly throughout the Commonwealth due to the complexity of local/sub-regional/regional flow systems, geologic structure, and land use activities. The type of groundwater use (residential, commercial, agricultural, mining, public water supply, irrigation) is also dependent on the chemical characteristics of the groundwater that is available to meet a need. For example, groundwater with elevated total dissolved solids may not be suitable for drinking water but can be used as process water for a mill or factory.

In Virginia's Coastal Plain and Eastern Shore, increasing concentrations of chloride and fluoride pose threats to portions of the Potomac and Yorktown Aquifers. Additional monitoring is needed to improve our understanding of how these concentrations are affected by groundwater withdrawals throughout the region. A 2011 peer review of Virginia's current Coastal Plain chloride monitoring network found inadequacies associated with coverage area and sampling frequency and recommended improvements (Mace, 2011). In other regions of Virginia, there is a general lack of data about the distribution and occurrence of naturally occurring contaminants of potential concern. Radionuclides are known to be distributed throughout the granitic and metamorphic aquifers of Virginia but to date, little has been done to characterize their extent. Although radionuclide detections are often below the Maximum Contaminant Limit (MCL), exceedences are not uncommon even within the relatively small percentage of wells historically sampled for this parameter. Arsenic above the Maximum Contaminant Level (MCL) has been noted in all of Virginia's provinces – most notably in the Mesozoic Basins of the Piedmont and in the Virginia Coastal Plain but mechanisms for the mobilization and distribution of arsenic in these diverse groundwater systems are poorly understood.

While some progress has been made in understanding the distribution and use of the groundwater resource in Virginia, a comprehensive groundwater sampling program is necessary to document existing water chemistry throughout the Commonwealth to advance our understanding of geologic controls on natural groundwater quality and how it is affected by dynamic variables such as climate, land use, and groundwater withdrawals.

Purpose and Scope

This document describes the network design and sampling strategy of a proposed groundwater monitoring program for characterizing and monitoring groundwater geochemical conditions throughout Virginia. The strategy document is meant to serve as a plan for distributing finite groundwater sampling resources throughout the state in the most efficient and scientifically defensible manner possible. Periodic revision to the sampling strategy will be directed by future monitoring results and evolving needs for groundwater quality data. An implementation plan will be prepared yearly; detailing what portions of the strategy will be accomplished depending on staffing and budgetary constraints.

Hydrogeology, Geology, and Groundwater Quality

This section briefly describes the geology and general groundwater conditions occurring across the five physiographic provinces of Virginia. Progressing from west to east these provinces are the Appalachian Plateaus, the Valley and Ridge, the Blue Ridge, the Piedmont, and the Coastal Plain (inset, figure 1).

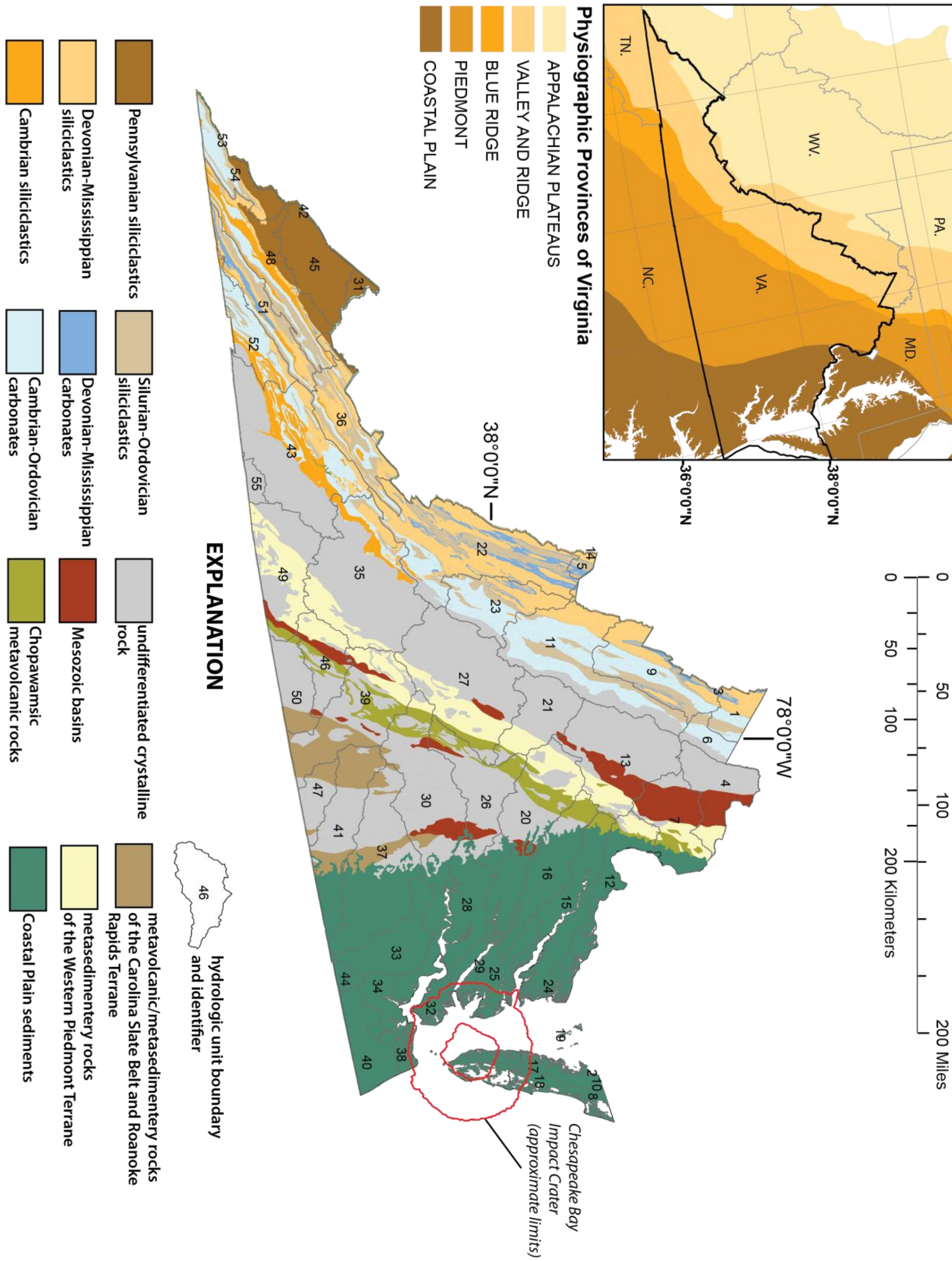


Figure 1: Distribution of the geochemical rock types and hydrologic units identified for the recommendation of monitoring wells in the portion of the state where groundwater is extracted primarily from fractured rock aquifers.

Appalachian Plateaus

The Appalachian Plateaus is a large physiographic region that encompasses many states east of the Mississippi River. It is bounded to the east by the folded and faulted Valley and Ridge province and to the west by nearly horizontal sedimentary rocks of the Interior Plains. During the late Paleozoic era, the region served as a depositional basin that received sediment washed westward off of uplifting mountains to the east. Burial and lithification resulted in the preservation of thousands of feet of sandstone, siltstone, shale, coal, and minor limestone. In Virginia, predominantly Pennsylvanian-age rocks of the Appalachian Plateaus are exposed in the southwest portion of the state, a region that encompasses all of Buchanan and Dickenson counties, and portions of Tazewell, Russell, Wise, Scott, and Lee Counties. The region is drained by the Levisa Fork, Tug, Powell, and Clinch rivers - all tributaries that feed the Ohio River which is the largest tributary of the Mississippi River drainage.

The same compressional forces that deformed the Valley and Ridge rocks to the southeast during the late Paleozoic also created a series of sub-parallel northwestward trending strike-slip faults in the plateaus region of Virginia. Movement along the fault systems resulted in the northwestward transport of a significant portion of Virginia's plateaus rocks on the order of 4-6 miles and the creation of several broad open folds throughout the region (McLoughlin, 1986). Other than strike-slip faulting however, the regional structure is relatively undeformed – principally broad, gentle folds, the dips of which are so slight, that in most parts of the region, the beds are essentially horizontal (Miller, 1974).

Subsequent uplift of the region has eroded and heavily dissected the gently dipping rocks in the plateaus resulting in a rugged topography of entrenched rivers, narrow valleys, steep hillslopes, and little or no bottomland (Harlow and Lecain, 1993). Shallow vertical and horizontal fractures develop locally along valley walls due to unequal stress relief associated with the action of down cutting rivers.

Well-cemented sandstone is ubiquitous throughout plateaus rock formations, therefore secondary permeability features such as bedding-plane separations, open fractures, and cleats found in coal beds account for the majority of groundwater movement in the region. Downward groundwater gradients exploit stress-relief fractures along valley walls and result in localized, shallow flow systems that ultimately discharge near valley floors. Regional groundwater movement is likely dominated by enhanced secondary permeability along coal-bed cleats. Groundwater transmissivity along coal seams have been shown to be one or two orders of magnitude greater than all other rock types or lithologic contacts in the plateaus and in general, transmissivity for all rock types decreased significantly at depths below 300 feet (Harlow and Lecain, 1993).

Valley and Ridge

The Valley and Ridge is a continuous physiographic province that extends from central Alabama northeastward to central Pennsylvania, a mostly linear belt of rocks covering approximately 46,000 square miles (Briel, 1997; Butts, 1940). In Virginia, rocks of the Valley and Ridge occupy nearly all of the western part of the state. In total, all or part of 26 counties from Frederick and Clarke counties in the north to Scott and Washington counties in the south are part of the Valley and Ridge province. The region is bordered on the southeast by igneous and metamorphic rocks of the Blue Ridge province and to the northwest by the nearly flat-lying, late-Paleozoic sedimentary rocks of the Appalachian Plateaus. The northern portion of Virginia's Valley and Ridge is drained to the Atlantic Ocean by the Shenandoah and James rivers whereas the portion south of Roanoke is drained to the Gulf of Mexico by the New River and tributaries of the Tennessee River.

The sedimentary rocks of the Valley and Ridge province in Virginia range from siliciclastic rocks such as shale, siltstone and sandstone, to carbonate rocks of limestone and dolostone. The depositional history of rocks in the province can be divided into two generalized time periods: 1) The Cambrian through early Ordovician period when vast thicknesses of calcium- and magnesium-carbonate sediments accumulated on an epicontinental shelf and 2) The Late Ordovician through Pennsylvanian period when influxes of thick wedges of predominantly siliciclastic sediments buried the shelf carbonates below several thousand feet of orogenically derived materials.

Intense deformation of the sedimentary rocks accommodated the predominantly northwest – southeast oriented compressional strain placed on the region as orogenic activity continued during the late Paleozoic era. Innumerable folds, faults and thrust sheets shortened and stacked blocks of the originally flat-lying sedimentary rocks on top of one another. Post-orogenic uplift and erosion of thousands of feet of overburden has exposed a topography characterized by broad carbonate valleys and sub-parallel ridges of coarse siliciclastic rocks.

Rock units in Virginia's Valley and Ridge have been characterized as having poor primary porosity due to cementation or poor sorting (Cady, 1936). Groundwater movement in the region is controlled by the structural orientation of bedding planes and other secondary permeability features such as joints and faults (Boughton and McCoy, 2006; Nelms and Moberg, 2010). In carbonate rocks, chemical dissolution enlarges these features and enhances transmissivity along preferential pathways forming conduits and submerged cave passages (Cady, 1936; Wright, 1990).

Blue Ridge and Piedmont

The Blue Ridge and Piedmont Physiographic Provinces occupy the central portion of Virginia and are bounded to the east by the onlap of Coastal Plain sediments at the Virginia Fall Zone and to the west by either fault or conformable contact with rocks of the Valley and Ridge province. To the north, the Blue Ridge and Piedmont are obscured by rocks of the Valley and Ridge in southern Pennsylvania and to the south by Coastal Plain sediments in eastern Alabama and western Georgia. The Blue Ridge and Piedmont provinces are comprised of Proterozoic to late Paleozoic crystalline rocks that have in places been rifted and infilled with early to mid Mesozoic sediments. These sediments have lithified into beds of sandstone, siltstone, and shale of varying thickness. In other places, the pre-existing rock of the Blue Ridge and Piedmont has been intruded by granitic rock of Proterozoic to Permian age. Several periods of high (amphibolite to granulite) grade regional metamorphosis of Blue Ridge and Piedmont rocks occurred throughout the Proterozoic and Palaeozoic Eras, and were primarily associated with periods of northwest directed crustal shortening accommodated by ductile deformation and faulting (Southworth et al., 2009). At least two periods of crustal extension occurred during this time but involved lower grade metamorphosis and displacement of pre-existing rock locally. With the exception of the siliciclastic rocks of the Mesozoic Basins, nearly all rocks of the Blue Ridge and Piedmont were originally crystalline or have been metamorphosed intensely enough to facilitate partial or total recrystallization. The Virginia Blue Ridge and Piedmont can be subdivided into distinct geologic units or terranes with characteristic mineralogies, textures, and ages. Common rock types in the Blue Ridge include granites, granitic gneisses, metamorphosed volcanic rock, and metamorphosed (crystalline) sedimentary rock of varying grain size. Rocks of the western and central Piedmont include metamorphosed (crystalline) sedimentary rocks and metamorphosed volcanic rocks. Rocks in the eastern portion of the Piedmont are comprised mainly of granites, granitic gneiss, and biotie and amphibolite gneisses. Rocks in the south-central Piedmont include less intensely metamorphosed volcanic and sedimentary rocks.

Rocks of the Blue Ridge and Piedmont have virtually no primary porosity and groundwater occurs in fractures of varying size, extent, and orientation. Fracturing in crystalline rock can be categorized into 3 major groups: 1) jointing associated with the reduction of pressure in the rock mass locally - jointing is directed by local stress fields in the rock established during emplacement and or deformation (Balk, 1937). Joint orientations are variable regionally but are often systematic locally (Bailey et al., 2003; White, 2012) 2) cleavage or parting along lineation in the rock established during regional deformation (Manda et al., 2008; Williams et al., 2005) 3) local fracturing of rock within and adjacent to fault planes (Johnston, 1962; Meinzer, 1923) . In the Mesozoic basins, fracturing is primarily associated with parting along bedding planes and jointing normal to bedding. Although the occurrence of groundwater in the fractured rock of the Virginia Blue Ridge and Piedmont is ubiquitous, the ability of these groundwater systems to transmit and store groundwater is highly variable and dependent on the extent and orientation of the fracture network, as well as the source of groundwater recharge to the fractured-rock groundwater system.

Coastal Plain

The Virginia Coastal Plain is located in eastern Virginia (Figure 1) and is comprised of a wedge-shaped package of eastward-thickening and eastward-dipping stratified sediments that are primarily unconsolidated (Figure 2). These sediments are of Cretaceous, Tertiary and Quaternary age, and unconformably overlie basement bedrock. The Coastal Plain sediments are bounded to the west by rocks comprising the Piedmont Physiographic Province at the Fall Zone where they constitute only a thin sediment cover. From the Fall Zone, they increase in thickness as they extend eastward across the continental shelf to their termination at the continental slope. To the north and south, the Virginia Coastal Plain sediments correlate with the larger Atlantic Coastal Plain Physiographic Province that spans from Massachusetts to the Gulf Coast of Alabama. McFarland and Bruce (2006) refined earlier hydrogeologic frameworks for the Virginia Coastal Plain to include recent geologic discoveries resulting from research into the Chesapeake Bay Impact Crater (Figure 1). McFarland and Bruce (2006) described a system of eight aquifers underlying portions of the Virginia Coastal Plain. This framework includes the unconfined surficial aquifer, the confined to semi-confined Yorktown-Eastover aquifer, and the confined aquifers of the Saint Marys, Piney Point, Aquia, Peedee, Virginia Beach, and Potomac. The Potomac and Aquia aquifers are truncated by the Chesapeake Bay Impact Crater, resulting in low permeability fine grain sediments of the Exmore Clasts, Exmore Matrix, and Chickahominy confining units that fill the crater being in direct contact with more highly permeable aquifer sediments.

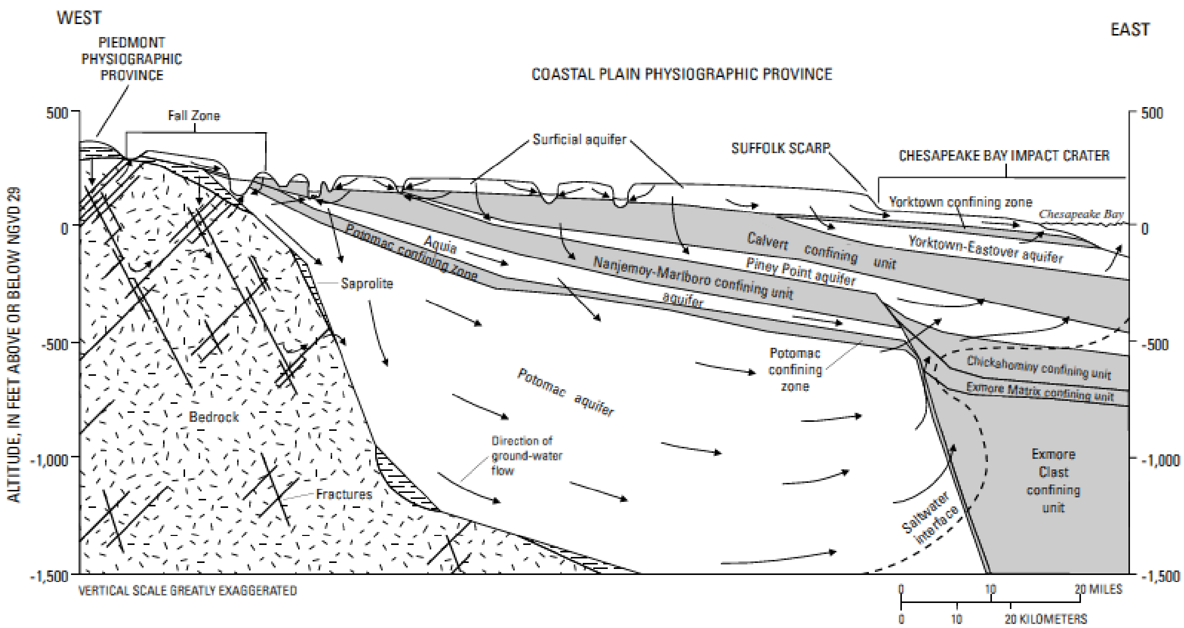


Figure 2: Generalized hydrogeologic section and directions of groundwater flow in the Virginia Coastal Plain (Altitude relative to National Geodetic Vertical Datum of 1929). (from McFarland and Bruce 2006).

The Cretaceous-age Potomac aquifer is the most utilized and productive water bearing unit in the Coastal Plain and is the only confined aquifer that is non-marine in origin, having been deposited in a fluvial environment. The water-bearing portions of it are typically comprised of quartz sand and gravel with a weathered, feldspar-derived clay binder. The other confined to semi-confined aquifers are all Tertiary-age marine deposits, and the most productive water-bearing portions are typically dominated by aragonitic and calcitic fossil shell material, and quartz sand and/or glauconitic sand. The Surficial aquifer is Quaternary to late-Tertiary in age and was deposited in fluvial terraces and flood plains. It is comprised principally of quartz sands and gravels with varying amounts of interbedded silts and clays.

Recharge of the entire Virginia Coastal Plain aquifer system is primarily from infiltration of precipitation into the water-table aquifer and downward leakage into the confined aquifer system principally along drainage divides between major river valleys (Figure 2). Water in the surficial aquifer eventually discharges into streams along valley lowlands resulting in little to no direct recharge at near-surface outcrop/subcrop portions of the hydrogeologic units (McFarland, 2010).

Groundwater movement in the Virginia Coastal Plain is controlled by the primary porosity between sediment grains of the more highly permeable formations that comprise the recognized aquifers. Less-permeable formations that restrict groundwater flow constitute confining units that separate the aquifers vertically from one another. This stratified relationship, coupled with the eastward dip of the formations, results in a horizontal hydraulic conductivity generally greater than the vertical hydraulic conductivity. Under pre-development conditions, this produced a generalized groundwater flow path from the Fall Zone, (along the thin western edge of the Coastal Plain near the interstate 95 corridor), down-dip to the east toward the saltwater transition/mixing zone, where fresh groundwater flowed upwards through overlying confining units to natural discharge zones near rivers and the coast (Figure 2). The movement of fresh groundwater has differentially flushed seawater from sediments around the Chesapeake Bay Impact Crater due to differences in permeability and along structural faults. This is evidenced by the presence of a chloride "mound" that conforms to the impact crater location. Additionally, across the impact crater, there are vertically inverted zones of decreasing chloride concentrations with depth, some of which form paths of differential flushing across and extending away from the impact crater (McFarland, 2010).

The dramatic increase in groundwater use in the Virginia Coastal Plain during the 20th century, caused groundwater flow to become redirected laterally towards locations of large groundwater withdrawals. In Virginia, large groundwater withdrawals have resulted in water level declines in some areas on the order of 200 feet, resulting in two major cones of depression centered on the paper production facilities at Franklin and West Point. This has reversed flow gradients from a previously seaward direction to a landward direction (Harsh and Laczniak, 1990) providing greater potential for saltwater intrusion. Although flow is now directed towards large withdrawal centers, the location of the current salt water transition zone results from pre-development conditions due to very low flow velocities that pumping has not yet displaced over appreciable distances (McFarland, 2010).

Heywood and Pope (Heywood and Pope, 2009) developed and calibrated a groundwater model for the mainland Virginia Coastal Plain based on the hydrogeologic framework outlined in Mcfarland and Bruce (2006) that incorporated the Chesapeake Bay Impact Crater and a single Potomac Aquifer. The stated primary purpose of their model is to predict changes in regional water levels in the confined aquifers in the Virginia Coastal Plain in response to future pumping. Additionally, they simulated the increased density of groundwater associated with the saltwater transition zone by modeling freshwater flushing that has occurred around the Chesapeake Bay Impact crater over the previous 108,000 years. However, the report states that their model is not currently capable of simulating or predicting temporal changes resulting from saltwater intrusion.

The revised hydrogeologic framework in McFarland and Bruce (2006) also included the Eastern Shore of Virginia (Figure 1). Sanford and others (2009) developed and calibrated a groundwater flow model for the Eastern Shore of Virginia to simulate groundwater level and salinity changes that can be anticipated in the future. The surficial aquifer and the upper, middle, and lower Yorktown-Eastover confined aquifers are utilized for freshwater supply on the Eastern Shore and each was incorporated into the model. In addition, the model incorporated two of four known paleochannels that influence the Eastern Shore hydrogeology. The model describes generalized groundwater flow on the Eastern Shore as originating from recharge on the upland areas along the central ridge of the Eastern Shore, moving downward and outward through the surficial aquifer to either discharge into the coastal bays or continue downward through each of the three consecutive underlying confining units and aquifers of the Yorktown-Eastover aquifer system. Water in the lower and middle Yorktown-Eastover aquifer is theorized to eventually flow back upward to discharge to the coastal bays with more shallowly circulating groundwater (Figure 3).

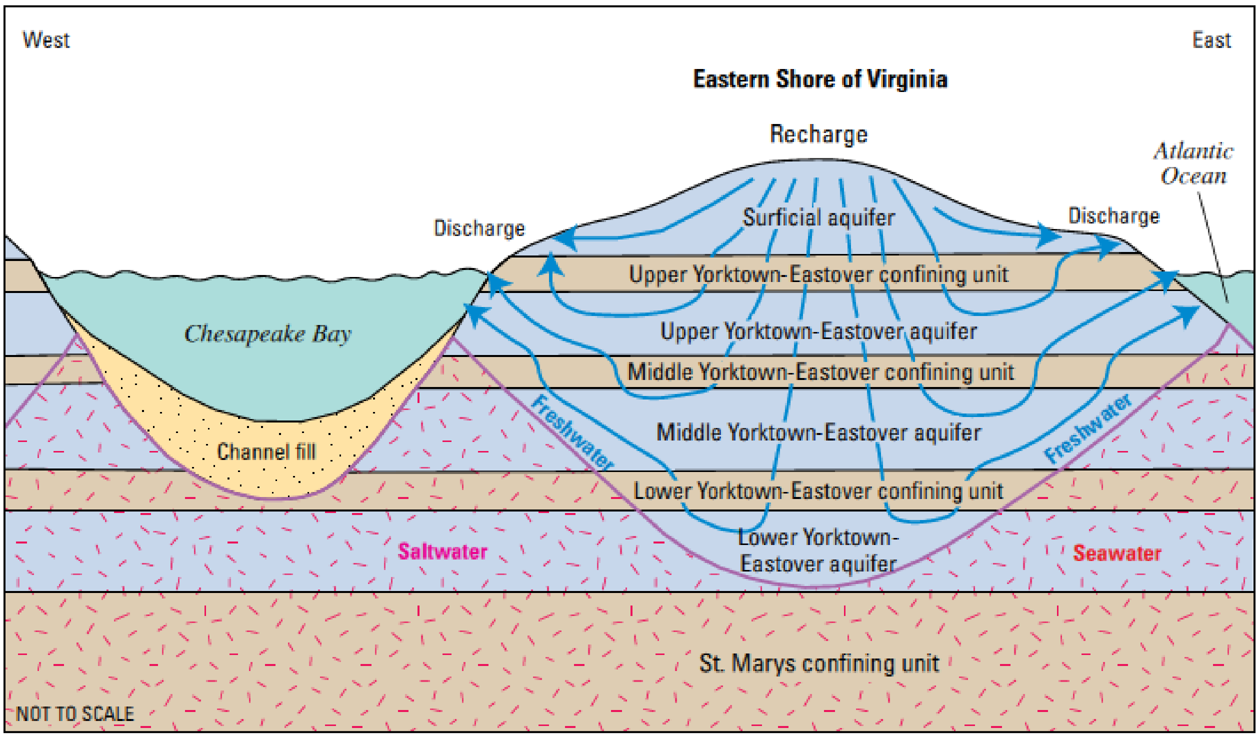


Figure 3: Generalized diagram of groundwater flow on the Eastern Shore of Virginia. (from Sanford et. al. 2009).

In addition to the typical groundwater flow path on the Eastern Shore, six paleochannels have been identified that incise the Virginia portion of the Eastern Shore (Colman et al., 1990; Krantz et al.; Oertel and Foyle, 1995) by offshore seismic studies (Figure 4). Three of these channels have been partially defined with borings onshore (Hobbs et al., 2011; Mixon, 1985). Additionally, a partially unfilled paleochannel is located almost entirely offshore of the southwestern tip of the Eastern Shore with open water depths in excess of 100 feet (Mixon, 1985; Sanford et al., 2009). This channel is incised deeply enough to possibly bring salty bay water into direct contact with the upper Yorktown-Eastover aquifer. The three defined onshore paleochannels are incised partially through the Eastern Shore but have been backfilled and buried as sea level rose following creation of the channels. The paleochannels are important because they are incised into the confined Yorktown-Eastover aquifer system and provide an avenue for saline water from the Chesapeake Bay and the Atlantic Ocean to enter portions of the Yorktown-Eastover confined aquifer system. Because coarse–grain, highly transmissive paleochannel sediments are likely in direct contact with portions of the incised Yorktown-Eastover aquifer, the likelihood for saltwater intrusion to occur is greater in these locations because of the direct connection to the Chesapeake Bay and Atlantic Ocean. If these paleochannels are also near large volume, groundwater withdrawal wells the likelihood for saltwater intrusion is even greater.

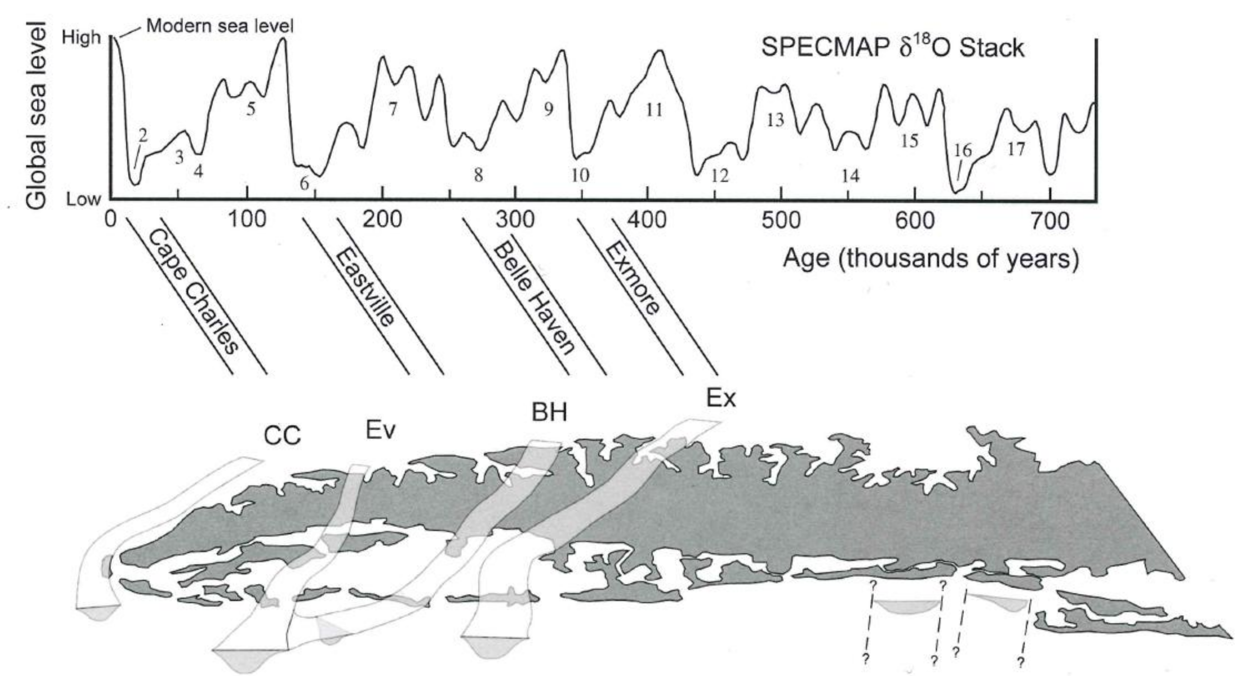


Figure 4: Six paleochannels identified on the Eastern Shore of Virginia through offshore seismic studies and their suspected correlations with δ^{18} O indicated sea level low stands (Krantz et al.).

Factors Affecting Groundwater Quality

Fractured-Rock Aquifers

Fractured-rock aquifers are available for utilization in all provinces of Virginia west of the Coastal Plain (inset, figure 1). Wells are occasionally drilled in fractured rock aquifers in the vicinity of the Fall Zone beneath Coastal Plain sediments (i.e. where sediments are thin and drilling depths to bedrock are not cost prohibitive).

Groundwater chemistry in fractured rock generally evolves from more oxygen rich, slightly acidic water with low ion concentrations in recharge areas to more mature, oxygen depleted, increasingly alkaline and solute-enriched groundwater in lower gradient and deeper portions of the groundwater flow system (Hem, 1992; Langmuir, 1997) . In fractured-rock groundwater systems, the change from recharge meteoric chemistry is controlled by the mineralogy, texture and structure of the host rock as well as the contact time and free energy available to drive chemical reactions. Groundwater chemistry evolves along structurally controlled flow paths in the fractured bedrock with significant departures in down-gradient chemistry resulting from the mixing of groundwater from different flow paths, changes in the mineralogy and texture of the host rock, and thermodynamic change along the groundwater flow path (Hem, 1992; Langmuir, 1997).

As a result of chemical and biochemical interactions between groundwater and the geologic materials through which it flows, and to a lesser extent because of contributions from the atmosphere and surface-water bodies, groundwater contains a wide variety of dissolved inorganic chemical constituents in various concentrations. The bulk of the chemical evolution of groundwater within the fractured rock portion of Virginia usually occurs in the upper portions of the groundwater flow system where freshly infiltrated meteoric water reacts with vegetatively and bacteriologically respirated carbon dioxide in the soil overburden to form carbonic acid (Equations 1 and 2) (Freeze and Cherry, 1979).

$$CO_2\,(g) + H_2O \leftrightarrow CO_2(aq) + H_2O \text{ Eq 1}$$

$$CO_2\,(g) + H_2O \leftrightarrow H_2CO_3(aq) \text{ Eq 2}$$

Carbonic acid is made available for reaction with the regolith and fractured-rock where it can dissociate into bicarbonate (Equation 3) and carbonate (Equation 4).

$$H_2CO_3(aq) \leftrightarrow H^+ + HCO_3^- \text{ Eq 3}$$

$$HCO_3^- \leftrightarrow H^+ + CO_3^{2-} \text{Eq 4}$$

The zone of most aggressive geochemical activity is largely coincident with the most notably weathered portions of the groundwater flow system – the regolith and upper portions of bedrock where hydrogen ions are actively transferred from solubilized acids and exchanged with freshly exposed minerals made available through persistent chemical and mechanical weathering. Aqueous reaction rates in deeper portions of the fractured bedrock flow system are usually slower as more minerals of the host rock come into chemical equilibrium with the groundwater, and the rock becomes harder to dissolve as available surface area is restricted to rock surfaces along fracture apertures (Hem, 1992; Langmuir, 1997).

While geochemical reactions in the fractured-rock portion of Virginia follow similar reaction paths, rock solubilities vary widely and are a major control on the natural solute concentration, pH, and buffering capacity of groundwater. Rocks of lower solubility usually have a silicate-based mineralogy and a crystalline mineral structure. These rocks are found exclusively within the Piedmont, Mesozoic Basins, and Blue Ridge and typically host lower pH groundwater with relatively low concentrations of dissolved minerals. Siliciclastic and carbonate rocks of the Valley and Ridge, Appalachian Plateaus, and Mesozoic Basins possess higher solubilities due to a non-crystalline structure. In some portions of the

Valley and Ridge, carbonate solubility has resulted in the creation of extensive voids and solution channels that serve as major groundwater reservoirs. In some cases, direct connection of these features with sinkholes and epikarst can result in rapid aquifer recharge and the introduction of anthropogenic contaminants to groundwater.

Recent regional groundwater analysis shows that calcium, magnesium, and sodium account for up to 90% of dissolved cation concentrations and bicarbonate alone accounts for over 80% of dissolved anion concentrations in igneous and metamorphic rocks of Virginia's Blue Ridge province (White, 2012). Similarly, median values of over 4,700 chemical analyses in the Valley and Ridge province from Pennsylvania to Alabama show that calcium and magnesium account for 92% of cations and bicarbonate alone accounts for over 80% of anions in solution. Calcium and bicarbonate were also found to be the dominant ions in solution for over 14,000 wells and springs sampled in the Piedmont of the eastern seaboard (Briel, 1997).

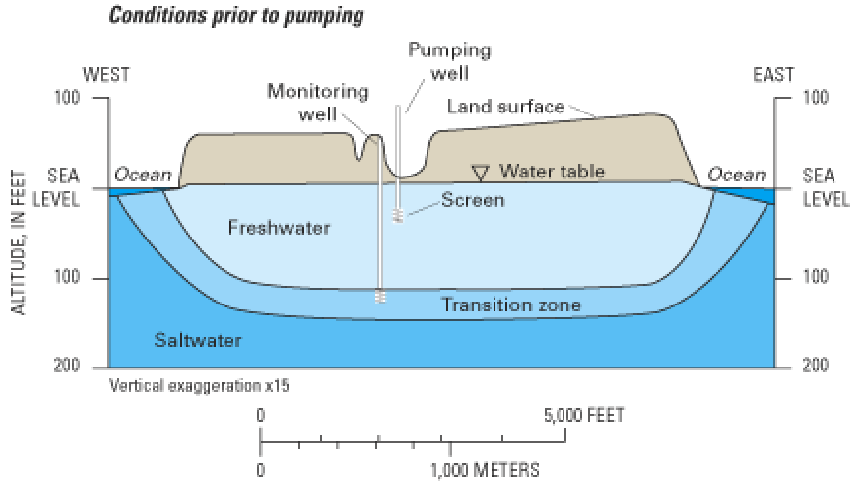
Coastal Plain Aquifers

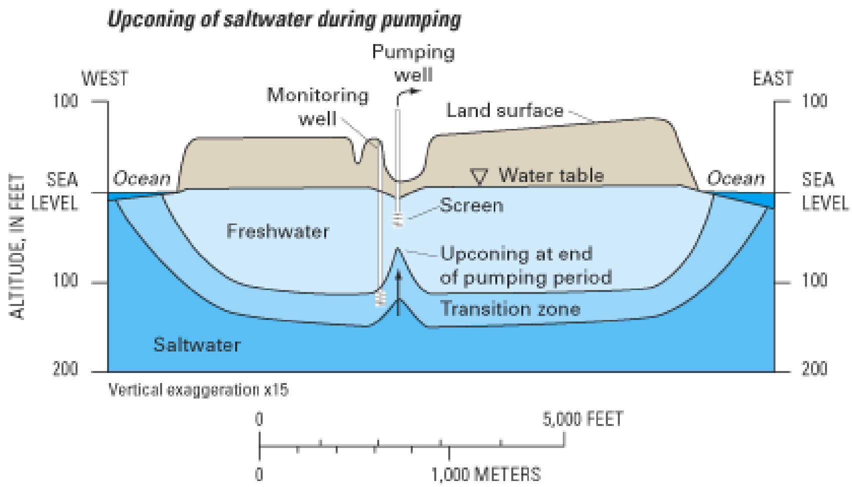
The hydrogeologic framework of the Coastal Plain of Virginia was most recently refined by McFarland and Bruce (2006) in order to incorporate geologic findings that resulted from research into the Chesapeake Bay impact crater. More recently, existing groundwater-quality data for the Virginia Coastal Plain was analyzed within the context of the refined hydrogeologic framework (McFarland, 2010). This work revealed that major ions in the groundwater in the deeper confined Coastal Plain aquifers (Piney Point, Aquia, and Potomac) vary eastward and with depth along groundwater flow paths. In general when examined from west to east, groundwater in these aquifers is dominated first by calcium/magnesium cations and bicarbonate/carbonate anions (hard water), then transitions to water dominated by sodium/potassium cations and bicarbonate/carbonate anions (soft water), and lastly to water dominated by sodium/potassium cations and chloride anions (salty water). McFarland (2010) attributed this to result from the hydrochemical facies concept first proposed by Back (Back, 1966). Back's concept postulates that the variations in water chemistry noted above develop from chemical weathering of sediments at depth, followed by ion exchange primarily with glauconite and clays, and finally from mixing with seawater along the saltwater transition zone as water moves eastward and down gradient along the groundwater flow path. McFarland (2010) also reported that the chemical composition of groundwater in the shallower Surficial and Yorktown-Eastover aquifers is more variable than in the deeper aquifers - likely attributable to short flow paths between recharge and discharge zones (McFarland and Bruce, 2006). Based on these findings, natural variation in groundwater chemistry in the mainland Virginia Coastal Plain is at least partially the result of its depth and location along the groundwater flow path between the recharge areas along the Fall Zone in the western Coastal Plain and the saltwater interface along the eastern Coastal Plain.

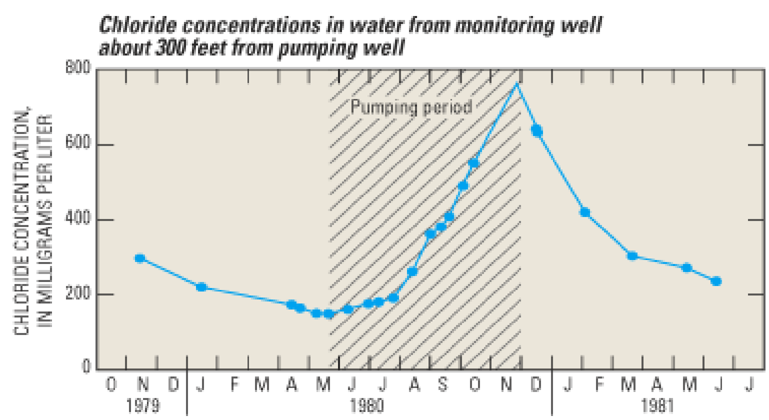
The constituents in groundwater that are of primary concern in the Virginia Coastal Plain are chloride and fluoride due to their health effects upon consumption. High concentrations of chloride are normally found in the eastern portions of the deeper aquifers, in wells suspected to withdraw close to or in the saltwater transition zone, and in shallower aquifers near brackish water. High fluoride concentrations are known from the upper part of the Potomac aquifer across a broad belt from south of the James River extending from the City of Franklin, across Suffolk, and to Chesapeake. The belt becomes narrower as it extends into Isle of Wight, Surry, James, and York counties and into the Middle Peninsula and Northern Neck (McFarland, 2010). Groundwater with high chloride or fluoride concentrations requires expensive treatment and/or dilution with other water sources in order to meet drinking-water standards.

Arsenic has also been a concern in several Coastal Plain public water-supply wells regulated by the Virginia Department of Health (VDH). Five wells in the Virginia Coastal Plain were listed by VDH as "may exceed" (4 wells) or as "likely to exceed" (1 well) a lowered arsenic Maximum Contaminant Level (MCL) on the basis of past samples before the US EPA implemented an MCL for arsenic of 10 ug/L in January, 2006 (previously it had been 50 ug/L) (Virginia Department of Health, 2005). A Maryland Geological Survey study (Drummond and Bolton, 2010) detected arsenic above 10 ug/L in parts of the Piney Point and Aquia aquifers. Elevated arsenic levels in the Maryland parts of these aquifers is limited to two narrow bands roughly parallel to formation strike, extending from the Maryland Eastern Shore into Southern Maryland. In Maryland, its presence correlates with the highest percentage of medium to coarse sand in the Aquia aquifer and sulfate concentrations below 10 mg/L, however the exact source of the Arsenic was not identified by the study. Two of the Lancaster County, Virginia wells identified by VDH as having potential arsenic problems correlate with the area identified in Maryland as having elevated arsenic levels in the Piney Point aquifer and one of these wells is confirmed to be screened in the Piney Point aquifer.

Saltwater intrusion is the introduction of saline water into freshwater aquifers. In Virginia, it is a problem unique to the Coastal Plain province. Saltwater intrusion results from man-made activities like over-pumping groundwater from coastal freshwater wells and the natural migration of the saltwater interface due to sea-level rise. Lowering of fresh groundwater levels through pumping of coastal wells allows denser saltwater to move farther inland, either laterally from the ocean and estuaries or upward from deeper brackish groundwater zones. Saltwater intrusion into highly utilized aquifers is a serious problem in many places along continental margins and often requires abandonment of wells when the concentration of dissolved ions in the water exceeds the user's ability to treat the water to drinking water standards (Hem, 1992). As a result, saltwater intrusion is recognized as a serious threat to coastal freshwater aquifers worldwide. Declining water levels and the threat of saltwater intrusion in southeast Virginia prompted establishment of the Commonwealth's first groundwater management area in 1973. Groundwater withdrawals from Virginia's Coastal Plain aquifer system have resulted in the reversal of hydraulic gradients toward large pumping centers, thereby potentially allowing lateral movement of the saltwater transition zone to occur. McFarland (2010) states that in Virginia, "Regional movement of the saltwater transition zone takes place over geologic time scales. Localized movement has been induced by groundwater withdrawal, mostly along shallow parts of the saltwater transition zone. Short term episodic withdrawals result in repeated cycles of upconing and downconing, which are superimposed upon longer term lateral intrusion" (see figures 5 and 6 for a generalized description of upconing, downconing, and lateral saltwater intrusion). Therefore, in terms of immediacy from a resource management perspective, upconing is likely to occur more frequently, potentially impacting wells in multiple limited areas, as opposed to the slower progressing lateral movement of the saltwater transition zone that is estimated to occur over geologic time scales.







Figures modified from LeBlanc and others (1986)

Figure 5: Typical example of saltwater upconing caused by pumping. Ground-water pumping from a well in the town of Truro on Cape Cod, Massachusetts, caused upconing of the transition zone beneath the well, which in turn caused increased chloride concentrations in a nearby monitoring well. After pumping at the well stopped in November 1980, the transition zone moved downward (downconing), and chloride concentrations at the monitoring well slowly decreased with time (Barlow, 2003).

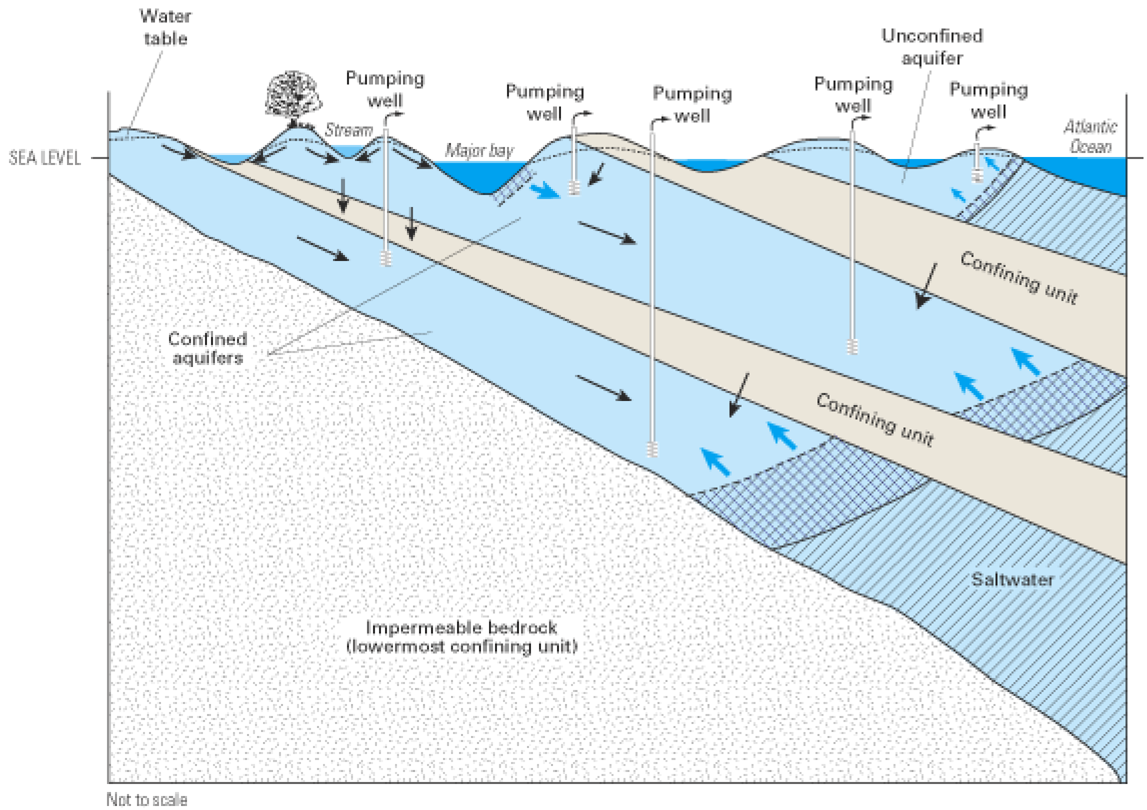


Figure 6: Typical modes of lateral saltwater intrusion in a multilayer Coastal Plain aquifer system. Saltwater moves into the unconfined aquifer from the Atlantic Ocean and into the shallow part of the top confined aquifer from the major bay. The two freshwater-saltwater interfaces at the seaward boundary of each of the confined aquifers also move landward as saltwater moves inland (Barlow, 2003).

Network Design Methodology

Recommendations for the placement of ambient groundwater network monitoring sites have been directed by methods designed to account for fundamental differences in the hydrogeologic framework and in regional monitoring requirements. In regions of the state where groundwater is primarily extracted from fractured-rock aquifers, a data-driven approach was utilized to recommend monitoring-well placement by watershed and rock type. In the Coastal Plain, monitoring locations were based on conclusions drawn from previous hydrogeologic and geochemical studies, and current chloride sampling efforts. The following sections describe the methods used to formulate monitoring-well placement in Virginia's Coastal Plain and its fractured-rock provinces. Details for the location, type, and sampling frequency of monitoring sites are presented in the "Conclusions and Network Design Recommendations" section.

Fractured-Rock Aquifers

Two assumptions were used to guide the site-selection methodology for the fractured-rock aquifer portion of Virginia: 1) natural variations in groundwater chemistry are largely controlled by rock solubility and mineralogy, and 2) most groundwater flow systems in fractured rock are restricted to major watershed boundaries. Incorporation of these assumptions into a systematic method for establishing groundwater quality monitoring stations has allowed an approach that recognizes the regional influences of geologic structure, lithology, and mineralogy on groundwater chemistry, and will allow data collected from these stations to be referenced at a watershed scale.

Digital versions of the 1993 State Geologic Map of Virginia (Virginia Division of Mineral Resources, 1993) and the Lithotectonic Map of the Appalachian Orogen (Hibbard et al., 2006) were used to subdivide the fractured rock portion of the state into distinct geochemical rock types based on mineralogy, lithology, and geologic history. Over 12,000 georeferenced archival groundwater samples(White et al., 2013) were grouped by geochemical rock type and analyzed for differences in specific conductance and the ratio of calcium to bicarbonate (Ca^{2+}/HCO_3^-) in milliequivalents (meq). Median values of the specific conductance and Ca^{2+}/HCO_3^- parameters were then cross plotted to generate geochemical markers for each rock type grouping that described the relative solubility and relative differences between calcium and bicarbonate- the most prevalent solubilized ions within the study area (Briel, 1997). Groundwater samples were rejected from the analysis if the calculated milliequivalent charge balance for major ions (Ca^{2+}, Mg^{2+}, Na^+, K^+, HCO_3^-, SO_4^{2-}, Cl^-, and F^-) was greater than 10% from equilibrium (total cation meq had to be within 10% of total anion meq for usable samples). For the initial analysis, seventeen rock-type subdivisions were created within the Piedmont and Blue Ridge, and fifty-two formational subdivisions were created for the Valley and Ridge and Appalachian Plateaus. Ultimately, five rock-type subdivisions in the Piedmont and Blue Ridge and six rock-type subdivisions in the Valley and Ridge and Appalachian Plateaus remained due to similarities between many of the geochemical markers and data limitations (a lack of statistically significant data for some of the rock types or formation groupings). The cross plot of median specific conductance and median ratios of calcium to bicarbonate by geochemical rock type are shown in figure 7. The corresponding map depicting the distribution of these geochemical rock types is shown in figure1.

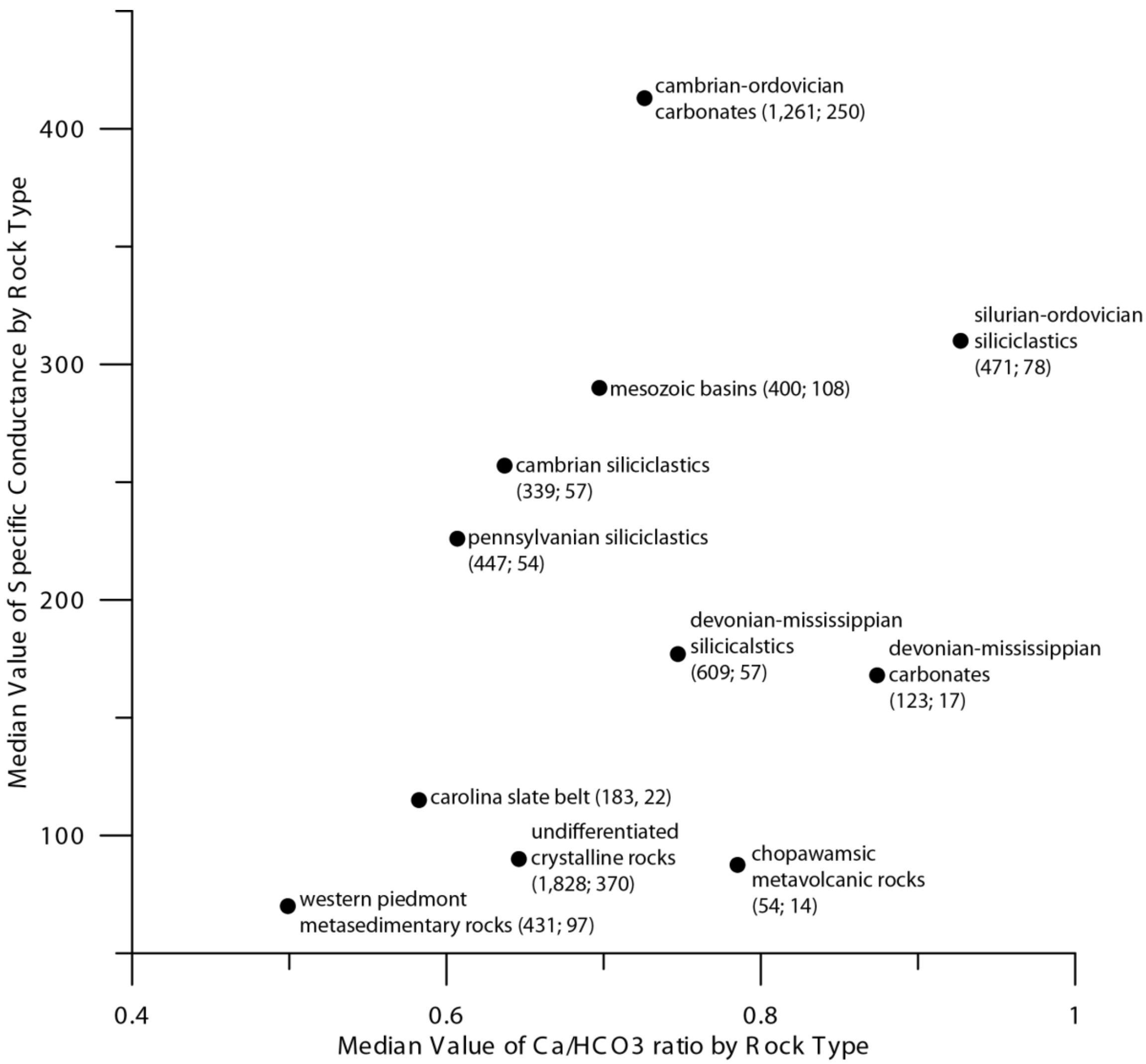


Figure 7: Crossplots of median values for specific conductance (y-axis), and calcium/bicarbonate ratio (x-axis) by geochemical rock type. Values in parentheses are numbers of values in the specific conductance and calcium/bicarbonate ratio data sets (respectively) used to generate the median value.

To identify the most prevalent geochemical groups at the watershed scale, a hydrologic unit map of the major watersheds in the Appalachian Plateaus, Valley and Ridge, Blue Ridge, and Piedmont (Steeves and Nebert, 1994) was overlain on the geochemical group map so that relative proportions of rock types could be quantified. Total areas of rock type by watershed were then calculated with a geographic information system (GIS) and assigned a percentage of total hydrologic unit area. Rock types comprising 15% or more of the total rock area within each watershed were flagged as eligible for a trend network well. Bivariate mapping of the fractured-rock portion of Virginia by watershed and rock type provides a method for evenly distributing trend well locations and allows for the collection and analysis of trend data at both the regional and local (watershed) level. While this site selection method may overlook ambient groundwater quality conditions occurring in larger watersheds with homogenous distributions of geochemical rock types, trend analysis will target and evaluate for trends as they relate to particular rock types and regions. Where watersheds have multiple trend wells, trend comparisons can be made at the watershed level. Archival data was also used to determine areas of the state with a paucity of groundwater-quality data. Figure 8 illustrates the current distribution of groundwater samples in ionic equilibrium, (where major cation milliequivalents are within 10% of major anion milliequivalents) and are considered to be representative of ambient groundwater conditions. In portions of the Coastal Plain and Northern Virginia, densities range from one groundwater sample location per 1.5 to 3 square miles, while throughout substantial portions of the south-side Piedmont and southwest Virginia, no quality groundwater-sample data exist. Throughout much of the state, ambient groundwater sample data range in availability from 1/20 mi^2 to 1/50mi^2. The "Conclusions and Network Design Recommendations" section details how prioritized spot sampling will be used to improve statewide sample coverage.

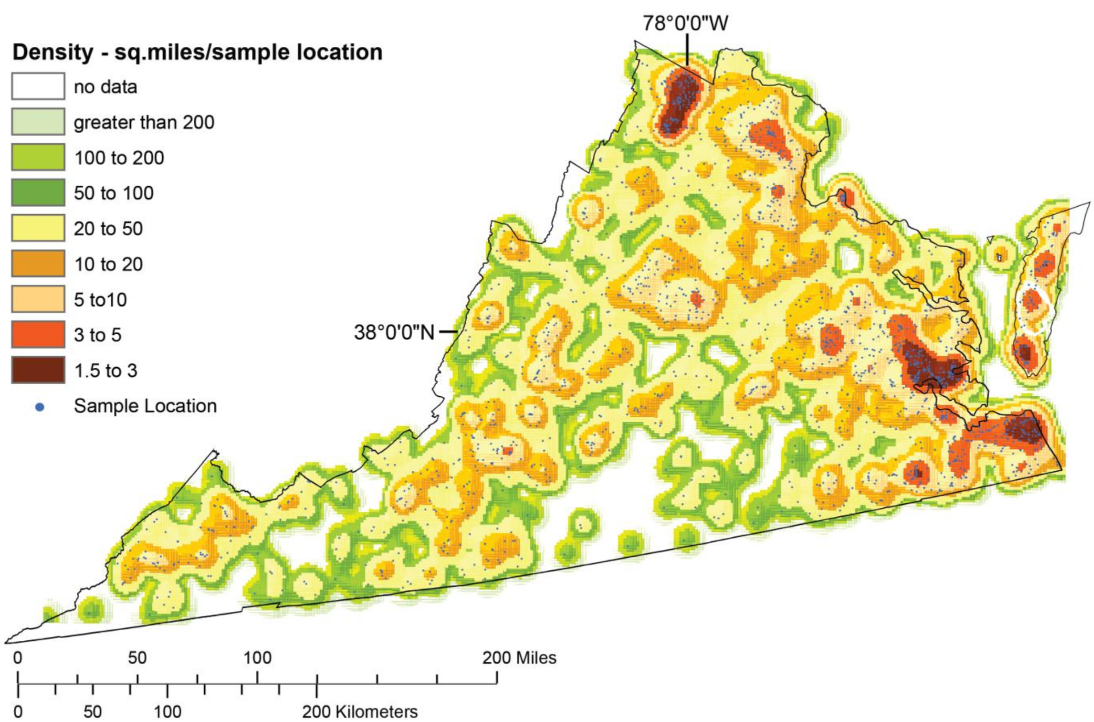


Figure 8: Density distribution of groundwater samples in the DEQ ambient groundwater geochemistry dataset.

Trend and Frequency Analysis of Archival Data

To assess the viability of an ambient groundwater trend-monitoring network in the fractured-rock aquifers of Virginia, the archival sample dataset was culled to find locations that had water-quality measurements over time. Out of the roughly 12,000 samples in the dataset, 84 groundwater wells and springs in the fractured-rock provinces had sufficient samples of acceptable quality to be analyzed for long-term trends and variance in groundwater-solute concentrations. Specific conductance values and the calcium to bicarbonate ratio for individual wells were plotted against a time-dependent axis from wells with multiple groundwater samples (Appendix A). Data for individual wells were then analyzed for trends over the corresponding time period using the Mann-Kendall trend test (Kendall, 1975; Mann, 1945). A computer program developed by the United States Geological Survey (Helsel et al., 2006) was used to generate each trend analysis. Archival geochemical data were also investigated for seasonal and episodic variance in natural groundwater chemistry.

Forty two of the 84 wells evaluated for long-term trends in groundwater chemistry demonstrated either an increasing or decreasing trend in specific conductance or the Ca^{2+}/HCO_3- ratio for the period record, 31 of 84 wells exhibited variable specific conductance values or Ca^{2+}/HCO_3- ratios with no discernible trend for the period of record, and only 11 of the 84 evaluated wells were found to be stable over the period of record (Figure 9, Table 1a-c, Table 2a-b, Table 3, Appendix A).

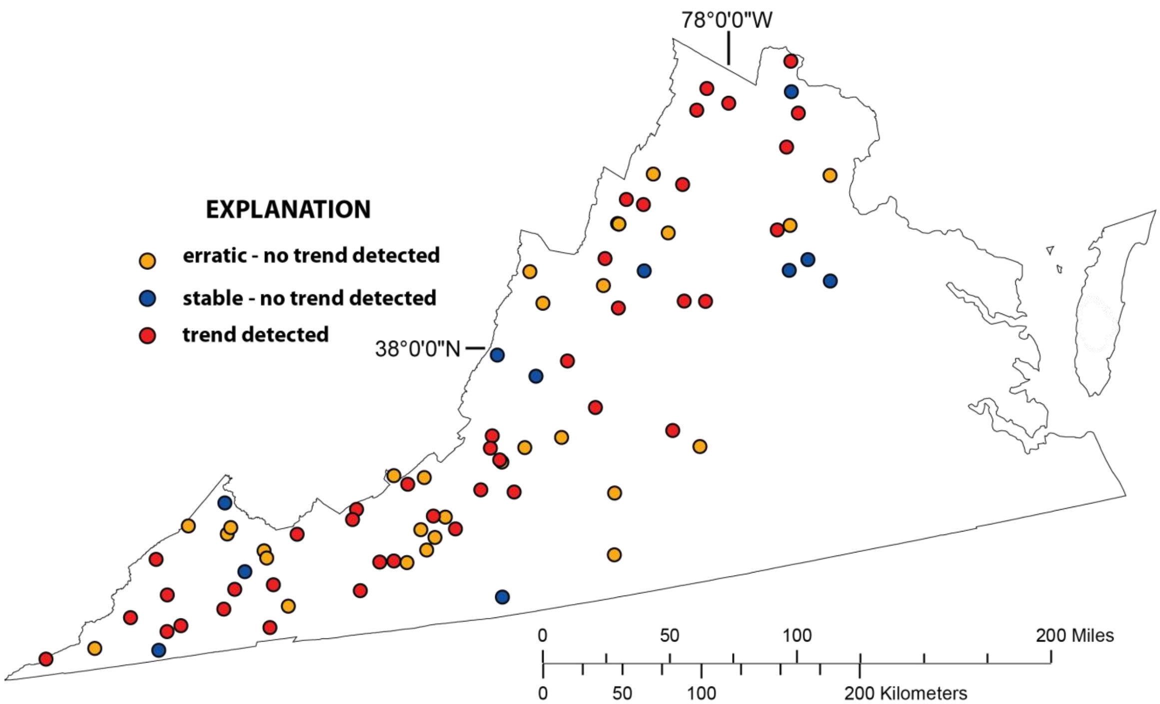


Figure 9: Distribution of wells analyzed for trend, and color-coded results of the Mann-Kendall trend analysis.

Table 1a: Mann-Kendall statistical test details for wells and springs in various rock-type groupings.

DEQ or USGS Well	Number of Measurements	Parameter	Period of Record	Trend	Tau	S	Z	p	Calculated Trend Equation
Undifferentiated Crystalline									
101-00182	25	specific conductance	9/22/1977 to 12/21/1992	increasing	0.287	86	1.985	0.0471	Y = -345.70 + 0.3016E-01 * X
101-00182	25	Ca/HCO3 ratio	9/22/1977 to 12/21/1992	decreasing	-0.367	-110	-2.547	0.0109	Y = 1.5789 + -0.2232E-04 * X
101-00183	32	specific conductance	2/2/1977 to 12/21/1992	increasing	0.367	182	2.93	0.0033	Y = 23.725 + 0.6347E-02 * X
101-00183	32	Ca/HCO3 ratio	2/2/1977 to 12/21/1992	increasing	0.397	197	3.181	0.0015	Y = 0.14228 + 0.2059E-04 * X
104-00139	7	specific conductance	6/29/1987 to 10/17/1990	decreasing	-0.905	-19	-2.703	0.0069	Y = 33890 + -16.95 * X
104-00139	7	Ca/HCO3 ratio	6/29/1987 to 10/17/1990	no trend	-0.524	-11	-1.502	0.1331	
109-00093	11	specific conductance	7/31/1980 to 10/12/1988	no trend	0.109	6	0.39	0.6962	
109-00093	11	Ca/HCO3 ratio	7/31/1980 to 10/12/1988	no trend	0.036	2	0.079	0.9372	
116-00208	5	specific conductance	8/13/1985 to 7/21/1988	no trend	-0.2	-2	-0.245	0.8065	
116-00208	6	Ca/HCO3 ratio	8/13/1985 to 7/21/1988	no trend	-0.2	-3	-0.376	0.7071	
Mesozoic Basins									
130-00535	5	specific conductance	3/31/1986 to 11/15/1988	no trend	0.6	6	1.225	0.2207	
130-00535	7	Ca/HCO3 ratio	3/31/1986 to 11/15/1988	increasing	0.714	15	2.103	0.0355	Y = -8.5536 + 0.3904E-03 * X
153-00176	6	specific conductance	8/14/1985 to 11/16/1988	increasing	1	15	2.63	0.0085	Y = -112.61 + 0.1200E-01 * X
153-00176	8	Ca/HCO3 ratio	8//14/1985 to 11/16/1988	no trend	0.214	6	0.619	0.5362	
153-00523	6	specific conductance	8/14/1985 to 11/16/1988	no trend	0.467	7	1.127	0.2597	
153-00523	7	Ca/HCO3 ratio	8/14/1985 to 11/16/1988	increasing	0.619	13	1.802	0.0715	Y =-0.37666 + 0.2711E-04 * X
153-00544	4	specific conductance	4/7/1986 to 11/16/1988	no trend	0.667	4	1.019	0.3082	
153-00544	5	Ca/HCO3 ratio	4/7/1986 to 11/16/1988	no trend	0	0	0	1	
171-00094	8	specific conductance	3/4/1986 to 10/18/1990	no trend	-0.143	-4	-0.371	0.7105	
171-00094	8	Ca/HCO3 ratio	3/4/1986 to 10/18/1990	no trend	0.071	2	0.124	0.9015	
Chopawamsic Metavolcanic									
105-00112	8	specific conductance	12/17/1980 to 7/21/1988	no trend	-0.286	-8	-0.866	0.3865	
105-00112	8	Ca/HCO3 ratio	12/17/1980 to 7/21/1988	no trend	-0.143	-4	-0.371	0.7105	
168-00214	5	specific conductance	8/22/1985 to 10/12/1988	increasing	0.9	9	2.021	0.0433	Y = -554.17 + 0.2384E-01 * X
168-00214	5	Ca/HCO3 ratio	8/22/1985 to 10/12/1988	decreasing	-0.8	-8	-1.715	0.0864	Y = 2.3421 + -0.5490E-04 * X
188-00046	5	specific conductance	8/8/1985 to 10/6/1988	no trend	-0.2	-2	-0.245	0.8065	
188-00046	7	Ca/HCO3 ratio	8/8/1985 to 10/6/1988	no trend	0.238	5	0.601	0.548	
188-01220	6	specific conductance	12/17/1980 to 7/21/1988	no trend	0.6	9	1.503	0.1329	
188-01220	7	Ca/HCO3 ratio	12/17/1980 to 7/21/1988	no trend	0.429	9	1.202	0.2296	
Western Piedmont Metasedimentary									
105-00076	6	specific conductance	9/4/1986 to 7/19/1990	no trend	0.067	1	0	1	
105-00076	6	Ca/HCO3 ratio	9/4/1986 to 7/19/1990	increasing	0.867	13	2.254	0.0242	Y = -1.7455 + 0.7565E-04 * X
168-00054	6	specific conductance	8/22/1985 to 10/12/1988	no trend	0.6	9	1.503	0.1329	
168-00054	8	Ca/HCO3 ratio	8/22/1985 to 10/12/1988	no trend	-0.071	-2	-0.124	0.9015	
170-00016	6	specific conductance	11/22/1988 to 11/8/1990	no trend	0.067	1	0	1	
170-00016	6	Ca/HCO3 ratio	11/22/1988 to 11/8/1990	no trend	0.067	1	0	1	
171-00013	7	specific conductance	1/7/1988 to 7/12/1990	no trend	-0.333	-7	-0.901	0.3675	
171-00013	7	Ca/HCO3 ratio	1/7/1988 to 7/12/1990	no trend	0.071	2	0.124	0.9015	
175-00014	4	specific conductance	7/30/1985 to 5/28/1987	no trend	0.667	4	1.019	0.3082	
175-00014	4	Ca/HCO3 ratio	7/30/1985 to 5/28/1987	no trend	0	0	0	1	
Cambrian Siliciclastics									
39S 14	10	specific conductance	9/8/1994 to 4/17/2000	no trend	0	0	0	1	
160-00310	21	specific conductance	2/18/1982 to 3/12/1990	no trend	-0.083	-21	-0.528	0.5974	
160-00310	12	Ca/HCO3 ratio	8/31/1982 to 3/12/1990	decreasing	-0.364	-24	-1.577	0.1148	Y = 1.5830 + -0.3419E-04 * X
177-00018	31	specific conductance	6/5/1980 to 12/13/1990	no trend	0.047	22	0.357	0.721	
177-00018	14	Ca/HCO3 ratio	6/5/1980 to 6/14/1990	no trend	0.121	11	0.547	0.5841	
177-00081	8	specific conductance	6/5/1980 to 11/13/1986	no trend	0	0	0	1	
183-00086	16	specific conductance	9/13/1989 to 10/29/1992	increasing	0.425	51	2.253	0.0242	Y = -1821.6 + 0.8040E-01 * X
183-00086	6	Ca/HCO3 ratio	1/4/1990 to 10/29/1992	N/A	-0.6	-9	-1.503	0.1329	
192-00119	17	specific conductance	9/11/1989 to 2/4/1993	increasing	0.125	17	0.66	0.5095	Y = -2870.8 + 0.1217 * X
192-00119	8	Ca/HCO3 ratio	11/6/1989 to 10/8/1992	no trend	0.286	8	0.866	0.3865	
198-00019	8	specific conductance	9/7/1976 to 3/27/1979	increasing	0.571	16	1.993	0.0463	Y = -141.64 + 0.1263E-01 * X
198-00019	11	Ca/HCO3 ratio	9/27/1976 to 3/27/1979	no trend	-0.291	-16	-1.204	0.2288	

Table 1b: Mann-Kendall statistical test details for wells and springs in various rock-type groupings.

DEQ or USGS Well	Number of Measurements	Parameter	Period of Record	Trend	Tau	S	Z	p	Calculated Trend Equation
Devonian - Mississippian Carbonates									
145-00046	15	specific conductance	5/26/1982 to 4/14/1993	no trend	-0.029	-3	-0.099	0.9212	
145-00046	6	Ca/HCO3 ratio	11/24/1986 to 4/27/1992	no trend	-0.6	-9	-1.503	0.1329	
Devonian - Mississippian Siliciclastics									
108-00095	14	specific conductance	4/10/1984 to 4/14/1993	no trend	0.077	7	0.328	0.7426	
108-00095	8	Ca/HCO3 ratio	4/24/1986 to 9/21/1992	no trend	-0.071	-2	-0.124	0.9015	
110-00004	20	specific conductance	7/11/1989 to 2/18/1993	no trend	0.168	32	1.006	0.3145	
110-00004	11	Ca/HCO3 ratio	9/18/1989 to 7/6/1992	decreasing	-0.345	-19	-1.401	0.1611	Y = 13.662 + -0.3668E-03 * X
122-00007	7	specific conductance	11/19/1987 to 12/6/1990	increasing	0.619	13	1.802	0.0715	Y = -643.44 + 0.2575E-01 * X
122-00010	27	specific conductance	7/10/1980 to 12/7/1989	decreasing	-0.504	-177	-3.674	0.0002	Y = 853.21 + -0.1639E-01 * X
122-00010	21	Ca/HCO3 ratio	4/10/1980 to 12/7/1989	increasing	0.29	61	1.813	0.0699	Y =-0.10423 + 0.1310E-04 * X
135-00133	8	specific conductance	3/3/1988 to 12/13/1990	no trend	-0.286	-8	-0.866	0.3865	
152-00034	19	specific conductance	8/28/1989 to 1/21/1993	no trend	0.064	11	0.35	0.7261	
152-00034	14	Ca/HCO3 ratio	10/25/1989 to 6/15/1992	increasing	0.275	25	1.314	0.1889	Y =-0.57647 + 0.3461E-04 * X
160-00096	29	specific conductance	5/8/1980 to 3/8/1990	increasing	0.392	159	2.965	0.003	Y = -1254.7 + 0.6148E-01 * X
160-00096	22	Ca/HCO3 ratio	5/8/1980 to 3/8/1990	increasing	0.619	143	4.004	0.0001	Y = -1.3757 + 0.6035E-04 * X
180-00532	13	specific conductance	7/9/1987 to 12/20/1990	no trend	-0.156	-7	-0.537	0.5915	
180-00532	6	Ca/HCO3 ratio	8/8/1988 to 7/5/1990	no trend	-0.067	-1	0	1	
180-01012	14	specific conductance	8/20/1987 to 12/6/1990	decreasing	-0.341	-31	-1.642	0.1005	Y = 515.01 + -0.1456E-01 * X
180-01012	8	Ca/HCO3 ratio	8/20/1987 to 8/16/1990	decreasing	-0.714	-20	-2.351	0.0187	Y = 5.2550 + -0.1449E-03 * X
182-00101	43	specific conductance	6/10/1974 to 12/29/1992	increasing	0.769	694	7.256	0	Y = -649.40 + 0.2953E-01 * X
182-00101	33	Ca/HCO3 ratio	9/19/1977 to 12/29/1992	increasing	0.741	391	6.045	0	Y = -1.5375 + 0.6710E-04 * X
186-00022	18	specific conductance	9/20/1989 to 10/29/1992	decreasing	-0.333	-51	-1.903	0.057	Y = 408.43 + -0.6131E-02 * X
186-00022	13	Ca/HCO3 ratio	11/13/1989 to 10/29/1992	no trend	0.051	4	0.183	0.8548	
Pennsylvanian Siliciclastics									
113-00068	9	specific conductance	8/20/1974 to 11/9/1977	no trend	0.278	10	0.949	0.3428	
113-00170	14	specific conductance	12/11/1989 to 9/10/1992	no trend	-0.033	-3	-0.109	0.9128	
113-00170	14	Ca/HCO3 ratio	10/19/1989 to 9/10/1992	no trend	-0.231	-21	-1.095	0.2736	
113-00171	15	specific conductance	12/11/1989 to 1/14/1993	no trend	-0.162	-17	-0.792	0.4285	
113-00171	10	Ca/HCO3 ratio	10/19/1989 to 1/14/1993	no trend	0.2	9	0.716	0.4743	
125-00165	17	specific conductance	12/6/1989 to 4/15/1993	no trend	0.044	6	0.206	0.8368	
125-00165	7	Ca/HCO3 ratio	2/12/1990 to 4/15/1992	no trend	0.429	9	1.202	0.2296	
125-00180	17	specific conductance	12/6/1989 to 4/15/1993	no trend	-0.206	-28	-1.12	0.2625	
125-00180	11	Ca/HCO3 ratio	10/17/1989 to 1/7/1993	decreasing	-0.327	-18	-1.327	0.1844	Y = 0.37972 + -0.6682E-05 * X
197-00301	11	specific conductance	8/14/1989 to 10/8/1991	increasing	0.345	19	1.401	0.1611	Y = -567.12 + 0.3327E-01 * X
197-00301	5	Ca/HCO3 ratio	2/8/1990 to 10/8/1991	no trend	-0.4	-4	-0.735	0.4624	
Silurian - Ordovician Siliciclastics									
107-00046	44	specific conductance	12/27/1976 to 3/30/1993	increasing	0.498	471	4.754	0	Y = -495.79 + 0.3886E-01 * X
107-00046	43	Ca/HCO3 ratio	12/27/1976 to 12/21/1992	increasing	0.386	349	3.643	0.0003	Y =-0.22481 + 0.3491E-04 * X
195-00020	21	specific conductance	4/29/1974 to 1/28/1993	decreasing	-0.238	-50	-1.48	0.139	Y = 1544.9 + -0.2263E-01 * X
195-00020	15	Ca/HCO3 ratio	8/30/1989 to 1/28/1993	no trend	-0.143	-15	-0.693	0.4884	
197-00303	11	specific conductance	12/5/1989 to 12/14/1992	increasing	0.559	76	3.089	0.002	Y = -4710.0 + 0.1590 * X
197-00303	5	Ca/HCO3 ratio	12/5/1989 to 8/27/1992	increasing	0.345	19	1.401	0.1611	Y = -1.7937 + 0.6539E-04 * X
Cambrian - Ordovician Carbonates									
38Q 2	11	specific conductance	6/16/1993 to 6/28/2007	increasing	0.745	41	3.114	0.0018	Y = 134.27 + 0.8091E-02 * X
38Q 2	7	Ca/HCO3 ratio	6/16/1993 to 6/28/2007	no trend	0.048	1	0	1	
39S 2	11	specific conductance	4/13/1994 to 4/13/1999	decreasing	-0.727	-40	-3.045	0.0023	Y = 4799.2 + -0.1273 * X
39S 2	9	Ca/HCO3 ratio	4/13/1994 to 6/8/1995	no trend	0.056	2	0.104	0.917	
39S 9	10	specific conductance	4/13/1994 to 4/18/2000	no trend	-0.333	-15	-1.252	0.2105	
39S 9	7	Ca/HCO3 ratio	4/13/1994 to 6/7/1995	no trend	0.429	9	1.202	0.2296	
39S 4	11	specific conductance	4/14/1994 to 4/13/1999	no trend	-0.182	-10	-0.703	0.4822	
39S 4	6	Ca/HCO3 ratio	4/14/1994 to 6/8/1995	no trend	0.333	5	0.751	0.4524	
39S 19	10	specific conductance	9/7/1994 to 4/13/1999	no trend	-0.378	-17	-1.453	0.1463	
40S 2	6	specific conductance	7/15/1992 to 6/27/2007	increasing	0.467	21	1.789	0.0736	Y = 161.07 + 0.8399E-02 * X
40S 2	10	Ca/HCO3 ratio	7/15/1994 to 6/27/2007	increasing	0.733	11	1.879	0.0603	Y = 0.21414 + 0.1688E-04 * X
41U 1	10	specific conductance	7/21/1992 to 6/27/2007	no trend	0.133	6	0.449	0.6534	
41U 1	10	Ca/HCO3 ratio	7/21/1992 to 6/27/2007	no trend	0.156	7	0.537	0.5915	
110-00026	15	specific conductance	1/10/1990 to 10/22/1992	no trend	0.143	15	0.697	0.4859	
110-00026	16	Ca/HCO3 ratio	11/8/1989 to 10/22/1992	increasing	0.25	30	1.306	0.1917	Y =-0.11943 + 0.1906E-04 * X
111-00235	26	specific conductance	5/22/1980 to 8/9/1990	no trend	-0.132	-43	-0.926	0.3546	
111-00235	17	Ca/HCO3 ratio	8/27/1980 to 8/9/1990	no trend	-0.059	-8	-0.288	0.7731	
121-00211	39	specific conductance	8/20/1981 to 10/24/2008	increasing	0.572	424	5.12	0	Y = 245.02 + 0.8314E-02 * X
121-00211	9	Ca/HCO3 ratio	4/9/1984 to 9/22/1992	decreasing	-0.667	-24	-2.398	0.0165	Y = 1.5122 + -0.2008E-04 * X
134-00033	15	specific conductance	7/23/1981 to 6/3/2011	increasing	0.305	32	1.536	0.1245	Y = 363.60 + 0.1039E-01 * X
134-00033	10	Ca/HCO3 ratio	7/23/1981 to 9/22/1992	no trend	-0.2	-9	-0.716	0.4743	
134-00034	15	specific conductance	7/9/1981 to 8/12/2003	increasing	0.514	54	2.626	0.0086	Y = 116.82 + 0.1160E-01 * X
134-00034	8	Ca/HCO3 ratio	4/9/1984 to 9/23/1992	no trend	-0.286	-8	-0.866	0.3865	

Table 1c: Mann-Kendall statistical test details for wells and springs in various rock-type groupings.

DEQ or USGS Well	Number of Measurements	Parameter	Period of Record	Trend	Tau	S	Z	p	Calculated Trend Equation
Cambrian - Ordovician Carbonates (Continued)									
135-00060	13	specific conductance	9/10/1987 to 12/13/1990	decreasing	-0.385	-30	-1.769	0.0769	Y = 4415.5 + -0.1288 * X
135-00060	8	Ca/HCO3 ratio	9/10/1987 to 12/13/1990	no trend	0.429	12	1.361	0.1735	
152-00043	20	specific conductance	8/28/1989 to 1/21/1993	no trend	0.153	29	0.909	0.3634	
152-00043	14	Ca/HCO3 ratio	8/28/1989 to 1/21/1993	no trend	0.121	22	0.547	0.5841	
160-00317	23	specific conductance	11/17/1981 to 3/12/1990	no trend	0.055	14	0.343	0.7313	
160-00317	11	Ca/HCO3 ratio	5/26/1983 to 3/12/1990	no trend	0.273	15	1.09	0.2758	
169-00071	27	specific conductance	11/1/1983 to 12/20/2012	increasing	0.256	90	1.856	0.0635	Y = 170.74 + 0.2543E-02 * X
169-00071	10	Ca/HCO3 ratio	11/1/1983 to 4/13/1992	no trend	-0.422	-19	-1.61	0.1074	
177-00002	17	specific conductance	6/5/1980 to 2/7/1984	decreasing	-0.25	-34	-1.379	0.1679	Y = 407.87 + -0.8699E-02 * X
177-00002	10	Ca/HCO3 ratio	6/5/1980 to 8/17/1983	no trend	-0.044	-2	-0.09	0.9284	
177-00019	22	specific conductance	6/5/1980 to 12/3/1987	no trend	0.043	10	0.254	0.7996	
177-00019	11	Ca/HCO3 ratio	6/5/1980 to 12/3/1987	no trend	0.164	9	0.623	0.5334	
180-00023	23	specific conductance	10/7/1980 to 10/14/1986	decreasing	-0.467	-98	-2.932	0.0034	Y = 1315.6 + -0.3334E-01 * X
180-00023	11	Ca/HCO3 ratio	6/5/1980 to 12/3/1987	no trend	0.164	9	0.623	0.5334	
181-00172	11	specific conductance	4/10/1984 to 9/3/1992	increasing	0.345	19	1.401	0.1611	Y = 191.59 + 0.5274E-02 * X
181-00172	6	Ca/HCO3 ratio	4/24/1986 to 9/3/1992	no trend	-0.467	-7	-1.127	0.2597	
182-00128	9	specific conductance	5/7/1981 to 11/18/1987	no trend	0.083	3	0.21	0.8339	
184-00011	14	specific conductance	12/4/1989 to 12/7/1992	no trend	0	0	0	1	Y = 471.50 + 0.000 * X
184-00011	12	Ca/HCO3 ratio	12/4/1989 to 12/7/1992	no trend	-0.242	-16	-1.029	0.3037	
184-00015	13	specific conductance	2/15/1974 to 12/3/1991	increasing	0.564	44	2.623	0.0087	Y = -220.57 + 0.1811E-01 * X
184-00015	8	Ca/HCO3 ratio	11/21/1974 to 12/3/1991	decreasing	-0.786	-22	-2.598	0.0094	Y = 0.97523 + -0.1384E-04 * X
184-00072	14	specific conductance	12/4/1989 to 12/7/1992	increasing	0.374	34	1.809	0.0704	Y = -109.33 + 0.1274E-01 * X
184-00072	15	Ca/HCO3 ratio	10/5/1989 to 12/7/1992	no trend	0.029	3	0.099	0.9212	
186-00066	14	specific conductance	9/20/1989 to 3/17/1992	no trend	0.253	23	1.213	0.2252	
186-00066	8	Ca/HCO3 ratio	11/13/1989 to 3/17/1992	no trend	-0.071	-2	-0.124	0.9015	
195-00045	16	specific conductance	10/24/1989 to 1/28/1993	no trend	0.092	11	0.451	0.6522	
195-00045	13	Ca/HCO3 ratio	10/24/1989 to 1/28/1993	decreasing	-0.385	-30	-1.769	0.0769	Y = 2.1612 + -0.4709E-04 * X
198-00026	12	specific conductance	4/7/1975 to 1/9/1992	no trend	0.167	11	0.687	0.4919	
198-00026	6	Ca/HCO3 ratio	1/13/1976 to 1/9/1992	decreasing	-0.867	-13	-2.254	0.0242	Y = 1.2796 + -0.2331E-04 * X
198-00034	20	specific conductance	7/19/1989 to 11/2/1992	no trend	0.132	25	0.781	0.4348	
198-00034	19	Ca/HCO3 ratio	7/19/1989 to 11/2/1992	increasing	0.263	45	1.539	0.1237	Y = 0.23587 + 0.1035E-04 * X
198-00062	17	specific conductance	9/25/1989 to 11/2/1992	no trend	-0.125	-17	-0.66	0.5095	
198-00062	13	Ca/HCO3 ratio	11/14/1989 to 8/13/1992	no trend	0.128	10	0.549	0.583	

Table 2a: Trend and stability designations for wells and springs in various rock-type groupings.

DEQ or USGS Well Identifier	County	Latitude (NAD83)	Longitude (Nad 83)	Elevation (FT A.M.S.L.)	Well Depth (Ft)	Date of First Sample	Date of Last Sample	Period of Record (Years)	Mann Kendall Status Specific Conductance	Range Specific Conductance µS/cm @ 25°C	Mann Kendall Status Ca^{2+}/HCO_3^- ratio	Range Ca2+/HCO3- ratio	WQ Stability Designation
Cambrian Siliciclastic													
160-00310	Montgomery	37.050426	-80.443282	2140	345	2/18/1982	3/12/1990	8.1	no trend	517	Decrease	0.28	Trend
177-00018	Pulaski	37.022957	-80.593635	2090	169	6/5/1980	12/13/1990	10.5	no trend	117	no trend	0.18	Erratic
177-00081	Pulaski	36.963597	-80.663184	2140	363	6/5/1980	11/13/1986	6.4	no trend	104	N/A	0.06	Erratic
183-00086	Russell	36.912668	-82.018761	2040	290	9/13/1989	10/29/1992	3.1	Increase	165	N/A	0.11	Trend
192-00119	Tazewell	37.158217	-81.534057	2460	476	9/11/1989	2/4/1993	3.4	Increase	1187	no trend	1.14	Trend
198-00019	Wythe	36.932100	-80.899643	1975	400	9/7/1976	3/27/1979	2.6	Increase	23	no trend	0.08	Trend
39S14	Rockingham	38.536278	-78.961048	1632	62	9/8/1994	4/17/2000	5.6	no trend	133	N/A	0.07	Erratic
Cambrian - Ordovician Carbonate													
107-00113	Augusta	38.217481	-79.136523	1420	140	5/19/1975	3/6/1986	10.8	no trend	258	N/A	N/A	Erratic
107-00442	Augusta	38.257092	-78.835252	1150	135	6/11/2002	6/28/2007	5	N/A	55	N/A	0.04	Stable
110-00026	Bland	37.241548	-81.100187	2090	525	11/8/1989	10/22/1992	3	no trend	39	Increase	0.08	Trend
111-00235	Botetourt	37.424144	-79.873931	1440	304	5/22/1980	8/9/1990	10.2	no trend	390	no trend	0.13	Erratic
121-00211	Clarke	39.068193	-78.028380	460	N/A	8/20/1981	10/24/2008	27.2	Increase	103	Decrease	0.11	Trend
134-00033	Frederick	39.168506	-78.161666	655	N/A	7/23/1981	6/3/2011	29.9	Increase	158	no trend	0.22	Trend
134-00034	Frederick	39.062948	-78.261386	720	N/A	7/9/1981	8/12/2003	22.1	Increase	147	no trend	0.07	Trend
135-00060	Giles	37.333210	-80.720485	1940	616	9/10/1987	12/13/1990	3.3	Decrease	208	no trend	0.15	Trend
152-00043	Lee	36.701854	-83.033999	1680	392	8/28/1989	1/21/1993	3.4	no trend	218	no trend	0.07	Erratic
160-00317	Montgomery	37.123761	-80.498834	1960	345	11/17/1981	3/12/1990	8.3	no trend	462	no trend	0.10	Erratic
169-00071	Page	38.679881	-78.457492	755	N/A	11/1/1983	12/20/2012	29.2	Increase	134	no trend	0.15	Trend
177-00002	Pulaski	37.139124	-80.580024	1840	300	6/5/1980	2/7/1984	3.7	Decrease	44	no trend	0.37	Trend
177-00019	Pulaski	37.077849	-80.680851	2146	450	6/5/1980	12/3/1987	7.5	no trend	273	no trend	0.42	Erratic
180-00023	Roanoke	37.196029	-79.998546	1260	580	6/5/1980	12/3/1987	7.5	Decrease	155	no trend	0.42	Trend
181-00172	Rockbridge	37.847925	-79.477460	1100	N/A	4/10/1984	9/3/1992	8.4	Increase	46	no trend	0.19	Trend
182-00128	Rockingham	38.435707	-78.620428	930	N/A	5/7/1981	11/18/1987	6.5	no trend	36	N/A	0.11	Erratic
183-00049	Russell	36.999332	-81.931543	1920	320	9/13/1989	7/12/1990	0.8	N/A	36	N/A	0.04	Stable
184-00011	Scott	36.644622	-82.597900	1500	350	12/4/1989	12/7/1992	3	no trend	63	no trend	0.07	Stable
184-00015	Scott	36.738233	-82.523734	2160	557	2/15/1974	12/3/1991	17.8	Increase	205	Decrease	0.11	Trend
184-00072	Scott	36.759136	-82.423894	2100	804	10/5/1989	12/7/1992	3.2	Increase	35	no trend	0.08	Trend
186-00066	Smyth	36.779329	-81.670158	2200	207	9/20/1989	3/17/1992	2.5	no trend	33	no trend	0.15	Erratic
195-00045	Washington	36.679052	-81.816267	2080	67	10/24/1989	1/28/1993	3.3	no trend	218	Decrease	0.63	Trend
198-00026	Wythe	36.802100	-81.162406	2620	165	4/7/1975	1/9/1992	16.8	no trend	184	Decrease	0.18	Trend
198-00034	Wythe	36.939323	-80.997138	2270	365	7/19/1989	11/2/1992	3.3	no trend	166	Increase	0.07	Trend
198-00062	Wythe	36.913210	-80.812148	2203	510	9/25/1989	11/2/1992	3.1	no trend	381	no trend	0.06	Erratic
38Q 2	Augusta	38.360623	-79.090689	1360	138	6/16/1993	6/28/2007	14	Increase	37	no trend	0.07	Trend
39S 19	Rockingham	38.531778	-78.953348	1523	N/A	9/7/1994	4/13/1999	4.6	no trend	147	N/A	0.17	Erratic
39S 2	Rockingham	38.530978	-78.952448	1517	12	4/13/1994	4/13/1999	5	Decrease	90	no trend	0.23	Trend
39S 4	Rockingham	38.531778	-78.953348	1523	21	4/14/1994	4/13/1999	5	no trend	205	no trend	0.22	Erratic
39S 9	Rockingham	38.530978	-78.952448	1517	40	4/13/1994	4/18/2000	6	no trend	46	no trend	0.22	Erratic
40S 2	Rockingham	38.612380	-78.755855	1074	149	7/15/1993	6/27/2007	14	Increase	51	Increase	0.09	Trend
41U1	Shenandoah	38.765485	-78.647462	1129	235	7/21/1993	6/27/2007	13.9	no trend	62	no trend	0.30	Erratic
Devonian - Mississippian Carbonate													
102-00056	Alleghany	37.945431	-79.955498	1765	446	11/16/1989	11/28/1990	1	N/A	70	N/A	0.01	Stable
145-00046	Highland	38.361850	-79.630561	2560	N/A	5/26/1982	4/14/1993	10.9	no trend	66	no trend	0.17	Erratic
192-00008	Tazewell	37.096275	-81.779329	2120	320	12/16/1974	2/2/1983	8.1	N/A	228	N/A	0.09	Erratic
Devonian - Mississippian Siliciclastic													
102-00045	Alleghany	37.796259	-79.713010	1180	230	8/18/1987	3/29/1990	2.6	N/A	50	N/A	0.06	Stable
108-00095	Bath	38.180430	-79.578010	1585	N/A	4/10/1984	4/14/1993	9	no trend	137	no trend	0.26	Erratic
110-00004	Bland	37.190159	-81.137407	2160	100	7/11/1989	2/18/1993	3.6	no trend	157	Decrease	1.37	Trend
122-00007	Craig	37.516538	-80.084951	1250	243	11/19/1987	12/6/1990	3	Increase	68	N/A	0.06	Trend
122-00010	Craig	37.452926	-80.112175	1320	N/A	7/10/1980	12/7/1989	9.4	Decrease	160	Increase	0.15	Trend
135-00133	Giles	37.390156	-80.805757	1740	390	3/3/1988	12/13/1990	2.8	no trend	1015	N/A	1.15	Erratic
152-00034	Lee	36.680746	-83.377037	1700	200	8/28/1989	1/21/1993	3.4	no trend	27	Increase	0.11	Trend
160-00096	Montgomery	37.238506	-80.225985	1220	510	5/8/1980	3/8/1990	9.8	Increase	1257	Increase	0.68	Trend
180-00532	Roanoke	37.367367	-80.049124	1280	500	7/9/1987	12/20/1990	3.5	no trend	139	no trend	0.78	Erratic
180-01012	Roanoke	37.381256	-80.060512	1600	127	8/20/1987	12/6/1990	3.3	Decrease	38	Decrease	0.19	Trend
182-00101	Rockingham	38.655576	-78.869335	1150	110	6/10/1974	12/29/1992	18.6	Increase	214	Increase	0.44	Trend
186-00022	Smyth	36.905441	-81.749048	2250	419	9/20/1989	10/29/1992	3.1	Decrease	36	no trend	0.11	Trend

Table 2b: Trend and stability designations for wells and springs in various rock-type groupings.

DEQ or USGS Well Identifier	County	Latitude (NAD83)	Longitude (Nad 83)	Elevation (FT A.M.S.L.)	Well Depth (Ft)	Date of First Sample	Date of Last Sample	Period of Record (Years)	Mann Kendall Status Specific Conductance	Range Specific Conductance µS/cm @ 25ºC	Mann Kendall Status Ca^{2+}/HCO_3^- ratio	Range Ca2+/HCO3- ratio	WQ Stability Designation
Chopawamsic Metavolcanic													
105-00112	Prince Edward	37.261981	-78.672543	645	405	1/14/1988	10/11/1990	2.7	no trend	62	no trend	0.15	Erratic
168-00214	Orange	38.340703	-77.860561	320	160	8/22/1985	10/12/1988	3.1	Increase	25	Decrease	0.06	Trend
188-00046	Spotsylvania	38.151809	-77.687509	355	50	8/8/1985	10/6/1988	3.2	no trend	80	no trend	0.08	Stable
188-01220	Spotsylvania	38.113440	-77.830968	290	250	12/17/1980	7/21/1988	7.6	no trend	17	no trend	0.05	Stable
Mesozoic Basin													
130-00535	Fauquier	38.774190	-77.682674	400	622	3/31/1986	11/15/1988	2.6	no trend	75	Increase	0.82	Trend
153-00176	Loudoun	39.226564	-77.535956	375	725	8/14/1985	11/16/1988	3.3	Increase	40	no trend	0.06	Trend
153-00523	Loudoun	38.942667	-77.554730	345	190	8/14/1985	11/16/1988	3.3	no trend	80	Increase	0.06	Trend
153-00544	Loudoun	39.064614	-77.573619	355	185	4/7/1986	11/16/1988	2.6	no trend	68	no trend	0.10	Stable
171-00094	Pittsylvania	36.765419	-79.389142	660	200	3/4/1986	10/18/1990	4.6	no trend	32	no trend	0.14	Erratic
Pennsylvanian Siliciclastic													
113-00068	Buchanan	37.216194	-82.013204	1290	120	8/20/1974	11/9/1977	3.2	no trend	150	n/a	0.17	Erratic
113-00170	Buchanan	37.247666	-81.983206	1520	N/A	12/11/1989	9/10/1992	2.8	no trend	115	no trend	0.14	Erratic
113-00171	Buchanan	37.385167	-81.998485	1090	N/A	12/11/1989	1/14/1993	3.1	no trend	65	no trend	0.06	Stable
125-00165	Dickenson	37.291001	-82.273746	1460	65	12/6/1989	4/15/1993	3.4	no trend	339	no trend	1.06	Erratic
125-00180	Dickenson	37.135172	-82.529567	1600	N/A	12/6/1989	4/15/1993	3.4	no trend	318	Decrease	0.03	Trend
197-00301	Wise	36.935453	-82.486236	1990	279	8/14/1989	10/8/1991	2.2	Increase	204	no trend	0.01	Trend
Silurian - Ordovician Siliciclastic													
107-00046	Augusta	38.083394	-79.060832	1420	460	12/27/1976	3/30/1993	16.3	Increase	611	Increase	0.24	Trend
135-00009	Giles	37.354597	-80.598546	2260	125	9/10/1987	9/7/1989	2	N/A	297	n/a	0.26	Erratic
192-00138	Tazewell	37.055163	-81.766829	2140	365	11/6/1989	2/4/1993	3.2	no trend	197	no trend	0.05	Erratic
195-00020	Washington	36.815170	-82.113201	2350	255	4/29/1974	1/28/1993	18.8	Decrease	325	no trend	0.12	Trend
197-00303	Wise	36.841292	-82.761228	1700	120	12/5/1989	12/14/1992	3	Increase	227	Increase	0.09	Trend
Undifferentiated Crystalline													
101-00182	Albemarle	38.032943	-78.450128	430	305	9/22/1977	12/21/1992	15.3	Increase	821	Decrease	0.31	Trend
101-00183	Albemarle	38.055751	-78.596679	515	135	2/2/1977	12/21/1992	15.9	Increase	88	Increase	0.22	Trend
104-00139	Amherst	37.572084	-79.340245	910	150	6/29/1987	10/17/1990	3.3	Decrease	60	no trend	0.12	Trend
109-00093	Bedford	37.444584	-79.610519	2530	200	7/31/1980	10/12/1988	8.2	no trend	16	no trend	0.21	Erratic
116-00208	Caroline	38.012966	-77.560777	290	275	8/13/1985	7/21/1988	2.9	no trend	11	no trend	0.06	Stable
Western Piedmont Metasedimentary													
105-00076	Appomattox	37.375000	-78.838000	830	300	9/4/1986	7/19/1990	3.9	no trend	19	Increase	0.14	Trend
168-00054	Orange	38.352231	-77.765035	315	360	8/22/1985	10/12/1988	3.1	no trend	225	no trend	0.37	Erratic
170-00016	Patrick	36.643196	-80.200782	1325	345	11/22/1988	11/8/1990	2	no trend	24	no trend	0.09	Stable
171-00013	Pittsylvania	37.097079	-79.312753	640	160	1/7/1988	7/12/1990	2.5	no trend	148	no trend	0.21	Erratic
175-00014	Prince William	38.576657	-77.418710	265	100	7/30/1985	5/28/1987	1.8	no trend	27	no trend	0.34	Erratic

Table 3: Number and percentage of wells and springs in various rock-type groupings with changing or stable water quality profiles.

Rock Type Grouping	Long Term Statistical Trend	No Trend - Erratic	No Trend - Stable	Total Wells and Springs	% Stable Wells and Springs
Cambrian Siliciclastic	4	3	0	7	0
Cambrian -Ordovician Carbonate	17	12	3	32	9
Chopawamsic Metavolcanic	1	1	2	4	50
Devonian - Mississippian Carbonate	0	2	1	3	33
Devonian - Mississippian Siliciclastic	8	3	1	12	8
Mesozoic Basin	3	1	1	5	20
Pennsylvanian Siliciclastic	2	3	1	6	17
Silurian - Ordovician Siliciclastic	3	2	0	5	0
Undifferentiated Crystalline	3	1	1	5	20
Western Piedmont Metasedimentary	1	3	1	5	20
All	42	31	11	84	13

Long-Term Trends

While data from several wells showed trends over periods of a decade or more, trends associated with many wells span shorter periods of time (as few as 1.8 years) and may not truly verify the presence of a long-term trend in groundwater chemistry at the site. There are also a number of factors related to well deterioration, stagnation of borehole water, and improper purge techniques that can result in false positives for trends in groundwater geochemistry (U.S. Geological Survey, variously dated) . Despite these potential sources of error, a significant number of wells were shown to exhibit long-term trends and or a high degree of variability in sample parameter values, and it is unlikely that these phenomena are attributable exclusively to factors that mask the character of the formation water geochemistry. The presence of increasing or decreasing trends in at least one of two groundwater parameters for half of the archival sample sites in fractured-rock aquifers indicate that local, and possibly regional trends in groundwater geochemistry are occurring. A study of more recent groundwater geochemical trend data in southeastern Pennsylvania found that trends in ambient groundwater chemistry existed in at least 20% of wells in a state-wide network of groundwater quality monitoring stations for at least one of a number of major ions and physical parameters (Reese and Lee, 1999). Potential sources for true long-term trends and variability in groundwater geochemistry include local sources of contamination, changes in land use, shifting weather patterns, local climatic events, groundwater withdrawal and artificial recharge, and may be local or regional in scale (Hem, 1992; Kelly and Meyer, 2005; Puckett et al., 2011).

Seasonal and Episodic Variance in Groundwater Geochemistry

The variance in the geochemical data did not correlate with seasonal or episodic weather events, although the majority of sampling sites with trending or erratic water-quality patterns exhibited significant variability suggestive of seasonal or episodic influences. Failure to definitively correlate these phenomena is likely related to the resolution and consistency of the archival sample data. Although many wells had multiple associated groundwater samples, they were not taken at intervals that were consistent enough to allow effective correlation. Additional complications associated with correlation stem from a lack of locally available meteorological data at or near sample locations. Other authors have demonstrated both seasonal and episodic variation in natural groundwater chemistry in similar hydrogeologic settings through continuous logging of basic geochemical parameters and climatic variables (Chapman et al., 2005). Short-term episodic and longer-term seasonal fluctuations of groundwater elevations are common in observations wells throughout the fractured-rock provinces indicating that many aquifers in these regions respond rapidly to influxes of meteoric water at certain times of the year.

Coastal Plain Aquifers

The threat of salt water intrusion to Virginia's Coastal Plain aquifer system is a long-term concern that must be specifically targeted for monitoring in order to achieve advance detection of its occurrence and progression. Therefore, establishment of a network of groundwater monitoring stations in the Virginia Coastal Plain must facilitate detection of lateral and vertical saltwater movement. Virginia's early Chloride Monitoring Program was originally implemented by the State Water Control Board (SWCB) in the early 1970's as an effort to evaluate chloride levels in the confined aquifers of Virginia's Coastal Plain Physiographic Province. Chloride monitoring by the SWCB terminated in 1990 due to budget cuts and staff reductions. The USGS resumed chloride monitoring in 1995 as part of a cooperative effort with the Hampton Roads Planning District Commission until funding was discontinued in 2012. Currently, a limited chloride monitoring effort is being conducted by the USGS in cooperation with the Department of Environmental Quality (DEQ). Water samples are collected annually from a network of wells and tested for chloride concentration along with other primary constituents. The current network totals 130 wells, a subset of which is sampled on a rotating basis. Current funding levels allow for the USGS to collect and analyze up to 14 samples and one Quality Assurance / Quality Control (QA/QC) sample per year with priority given to wells with previous chloride levels above 100 mg/L.

In addition to the 130 wells currently monitored in the chloride monitoring network, the DEQ imposes monitoring requirements on some permitted wells operated by groundwater users in the management area. These requirements are imposed in order to help detect saltwater intrusion or water-quality changes resulting from groundwater withdrawals. Currently, 91 permitted wells are monitored in the Virginia Coastal Plain with testing frequency varying from monthly to annually and analysis including between one and 15 parameters. All 91 wells are monitored at least for chloride concentration but other required sample parameters can include calcium, fluoride, iron, magnesium, manganese, potassium, selenium, sodium, zinc, sulfate, alkalinity, pH, TDS, and total hardness. However, the individual parameters tested for and the testing frequency varies by well. Although these results do not meet the USGS requirements necessary to be accepted into their electronic data repository, DEQ plans to utilize these results to supplement the data collected by the chloride monitoring/ambient network.

Shortcomings of the current program identified by McFarland (2010) include the following observations: many of the wells are not optimally located for saltwater intrusion monitoring; sampling is not frequent enough to distinguish between short-term chloride increases due to vertical upconing and long-term increases due to lateral intrusion; and re-development of screened sediments in current monitoring wells may be required to ensure collection of truly representative water samples (McFarland, 2010). Despite these issues, sampling within the current chloride monitoring network has facilitated the delineation of the saltwater transition zone and identification of areas where rapid rates of increasing chloride concentrations have already occurred. Specific recommendations for sampling requirements to adequately characterize the aquifer systems of the Coastal Plain are detailed in the "Conclusions and Network Design Recommendations" section later in the report.

Analytes

Analytes were selected to characterize the natural geochemical conditions occurring in the fractured-rock and Coastal Plain aquifer systems of the Commonwealth. The suites of major ions, physical parameters, metals, and field parameters (Table 4a–c) were selected after discussions with laboratory representatives from the state lab (Division of Consolidated Laboratory Services), water-quality scientists from the DEQ Office of Water Monitoring and Assessment and the U.S. Geological Survey's Virginia Water Science Center. Several rounds of equipment blank testing were performed on various configurations of submersible sampling pumps and tubing in order to minimize contamination from sampling equipment. Although the purpose of the sampling program is to describe the natural chemical composition of Virginia's groundwater resources, some anthropogenic compounds (Table 4d) will be sampled for initially to verify that trend wells have been sited properly and are not impacted by point source contamination. Due to well construction and aquifer-specific considerations, metals analysis will not be included on every well sampled by the program.

Table 4a: Field parameters - all groundwater quality sites.

Field Parameters	Resolution
Acid Neutralizing Capacity (mg/L as $CaCO_3$)	0.1
Alkalinity, field (mg/L as CO_3^{2-})	0.1
Alkalinity, field (mg/L as HCO_3-)	0.1
Alkalinity, field (mg/L as OH^-)	0.1
Dissolved Oxygen (mg/L)	0.01
Fluid Resistivity (Ω-cm)	1
pH, field, standard units su	N/A
Salinity (ppt)	0.01
Specific Conductance (umhos/cm @ 25c)	1
Temperature °C	0.1
Total Dissolved Solids (G/L)	0.001
Turbidity,field, nephelometric turbidity units, ntu	0.01
Flow (Gallons/Min)	0.1
Stabilized Pumping Water Level (Ft)	0.1

Table 4b: Core schedule - all groundwater quality sites.

CORE Schedule	Method Detection Limit
pH, lab, standard units su	N/A
Specific Conductance (umhos/cm @ 25c)	N/A
Acid Neutralizing Capacity (mg/L as $CaCO_3$)	0.1
Acidity, total (mg/L as $CaCo_3$)	1
Alkalinity, Bicarbonate (mg/L as $CaCo_3$)	1
Alkalinity, Carbonate (mg/L as $CaCo_3$)	1
Bromide, Dissolved (mg/L as Br)	0.01
Calcium, dissolved (mg/L as Ca)	0.2
Carbon, total organic (mg/L as C)	0.4
Chloride,total in water (mg/L as Cl)	1
Color (platinum-cobalt units)	1
Flouride, Dissolved (mg/L as F)	0.1
Hardness, total (mg/L as $CaCo_3$)	1
Iodide, Dissolved (mg/L as I)	
Magnesium, dissolved (mg/L as Mg)	0.1
Nitrate nitrogen, total (mg/L as N)	0.01
Nitrite nitrogen, total (mg/L as N)	0.01
Phosphorus,in total orthophosphate (mg/L as P)	0.01
Potassium, dissolved (mg/L as K)	0.1
Residue, fixed filtrable (mg/L)	5
Residue, fixed nonfiltrable (mg/L)	1
Residue, total (mg/L)	5
Residue, total fixed (mg/L)	5
Residue, total nonfiltrable (mg/L)	1
Residue, total volatile (mg/L)	5
Residue, volatile filtrable (mg/L)	5
Residue, volatile nonfiltrable (mg/L)	1
Residue, total filtrable (dried at 105c), (mg/L)	5
Residue,total filtrable (dried at 180c),(mg/L)	5
Silica, dissolved (mg/L as si02)	0.02
Sodium, dissolved (mg/L as na)	0.2
Sulfate, total (mg/L as so_4)	1
Turbidity,lab nephelometric turbidity units, ntu	0.02

Table 4c: Trace metals analytes- selected groundwater quality sites.

Trace Metals	Method Detection Limit
Aluminum, dissolved (ug/L as Al)	0.1
Antimony, dissolved (ug/L as Sb)	0.01
Arsenic, dissolved (ug/L as As)	0.05
Barium, dissolved (ug/L as Ba)	4
Beryllium, dissolved (ug/L as Be)	0.02
Cadmium, dissolved (ug/L as Cd)	0.02
Calcium, dissolved (mg/L as Ca)	0.04
Chromium, dissolved (ug/L as Cr)	0.1
Copper, dissolved (ug/L as Cu)	0.01
Hardness, Ca Mg calculated (mg/L as $CaCo_3$)	0.22
Iron, dissolved (ug/L as Fe)	10
Lead, dissolved (ug/L as Pb)	0.01
Magnesium, dissolved (mg/L as Mg)	0.03
Manganese, dissolved (ug/L as Mn)	0.1
Mercury-tl,filtered water,ultratrace method ng/L	1.3
Nickel, dissolved (ug/L as Ni)	0.08
Potassium, dissolved (mg/L as K)	0.1
Selenium, dissolved (ug/L as Se)	0.2
Silver, dissolved (ug/L as Ag)	0.03
Sodium, dissolved (mg/L as na)	0.2
Thallium, dissolved (ug/L as Tl)	0.01
Uranium, dissolved (ug/L as U)	0.01
Zinc, dissolved (ug/L as Zn)	0.4

Table 4d: Anthropogenic Schedule for selected sites.

Anthropogenic Schedule	Method Detection Limit
Acetone (ug/L)	0.28
Acrylonitrile (ug/L)	0.22
Allyl Chloride (ug/L)	0.13
Benzene (ug/L)	0.03
Bromobenzene (ug/L)	0.11
Bromochloromethane (ug/L)	0.07
Bromodichloromethane (ug/L)	0.03
Bromoform (ug/L)	0.2
Bromomethane (ug/L)	0.06
2-Butanone (ug/L)	0.48
n-Butylbenzene (ug/L)	0.03
sec-Butylbenzene (ug/L)	0.12
tert-Butylbenzene (ug/L)	0.33
Carbon disulfide (ug/L)	0.09
Carbon tetrachloride (ug/L)	0.08
Chloroacetonitrile (ug/L)	0.12
Chlorobenzene (ug/L)	0.03
1-Chlorobutane (ug/L)	0.18
Chloroethane (ug/L)	0.02
Chloroform (ug/L)	0.02
Chloromethane (ug/L)	0.05
2-Chlorotoluene (ug/L)	0.05
4-Chlorotoluene (ug/L)	0.05
Dibromochloromethane (ug/L)	0.07
1,2-Dibromo-3-chloropropane (ug/L)	0.05
1,2-Dibromoethane (ug/L)	0.02
Dibromomethane (ug/L)	0.03
1,2-Dichlorobenzene (ug/L)	0.05
1,3-Dichlorobenzene (ug/L)	0.05
1,4-Dichlorobenzene (ug/L)	0.04
trans-1,4-Dichloro-2-butene (ug/L)	0.36
Dichlorodifluoromethane (ug/L)	0.11
1,1-Dichloroethane (ug/L)	0.03
1,2-Dichloroethane (ug/L)	0.02
1,1-Dichloroethene (ug/L)	0.05
cis-1,2-Dichloroethene (ug/L)	0.06
trans-1,2-Dichloroethene (ug/L)	0.03
1,2-Dichloropropane (ug/L)	0.02

Table 4d (continued): Anthropogenic Schedule for selected sites.

Anthropogenic Schedule	Method Detection Limit
Trichloroethene (ug/L)	0.02
Trichlorofluoromethane (ug/L)	0.07
1,2,3-Trichloropropane (ug/L)	0.03
1,2,4-Trimethylbenzene (ug/L)	0.02
1,3,5-Trimethylbenzene (ug/L)	0.02
Vinyl chloride (ug/L)	0.04
o-Xylene (ug/L)	0.06
m-Xylene (ug/L)	0.03
p-Xylene (ug/L)	0.06
Diesel Range Organics, Total in water (ug/L)	
Kerosene (ug/L)	

Sampling Procedures

DEQ Groundwater Characterization Program (GWCP) staff worked to develop consistent sampling procedures for wells and springs by examining guidelines established in the *National Field Manual for the Collection of Water-Quality Data* (U.S. Geological Survey, 2006), exploring procedures followed by ambient groundwater monitoring programs from other states, and consultation with DEQ's surface-water-quality scientists.

Groundwater samples will be collected from sites where well construction details are adequately known from water-well completion reports or through geophysical logging. Additional site work may be necessary at some sites to establish or update critical construction and hydrogeologic information including but not limited to: geophysical logging, camera surveying, pump testing, slug testing, and additional well development procedures to remove fluids introduced during the drilling and well construction process. Some wells may need to be redeveloped to remove particulate matter accumulations that can result in potential sampling bias (Lane et al., 2003; U.S. Geological Survey, 2006). In addition, prior to pumping/sampling wells in the Coastal Plain, fluid resistivity logs will be run on the undisturbed water column in the wells to document any natural chemical stratification that may develop between pumping events as more dense saltwater preferentially settles towards the bottom of the wells.

The depth and pumping rate of the sampling pump will be set to minimize the amount of stagnant borehole water above the pump intake and prevent dewatering of the borehole below the targeted production zone and entrainment of sediment. Samples will be collected after all of the following criteria are met: 1) quasi-steady state drawdown conditions are achieved, 2) three well volumes are discharged from the borehole, 3) field parameters are stabilized, (pH, electrical conductivity, dissolved oxygen, temperature, turbidity), and 4) turbidity falls below 50 nephelometric turbidity units (ntu). Once field criteria are met, the pumping rate will be decreased to allow for advection of fresh formation water above the pump. This will be done to further reduce potential sampling bias due to dilution of fresh formation water with stagnant borehole water that may remain above the pump. Following the decrease in pumping rate, samples will be collected after field criteria stability is again achieved and at least 10 sampling equipment volumes pass through the pump and tubing. Wells that require long purge times (> 10 hours) or where turbidity targets cannot be achieved will be avoided if possible or redeveloped to ensure adequate communication with the aquifer. If it is necessary to sample a well that takes multiple days to purge, at least one well volume should be extracted the day of sampling.

Spot sampling will likely include wells that have active pumps set at depths to maximize production characteristics for the well owner. In some cases, this will prohibit the collection of pumping water elevation data. Sampling at active supply wells will occur after field criteria 2 – 4 are achieved. Samples will be collected from a sample spigquot located before any treatment system or pressure tanks.

Unfiltered water samples will be collected for physical parameters, radionuclides, anthropogenics indicators, and total metals analyses. Trace metal and major ion samples will be processed through 0.4 micron trace-metal-certified filters prior to containerization. Pre-labeled sample containers will be filled in a manner that minimizes headspace. Chemical preservatives will be applied in accordance to laboratory directives and transferred immediately to iced coolers for transport. Filtered water will be used to perform a field alkalinity titration onsite prior to potentially significant shifts in alkalinity occur due to atmospheric gas exchange, depressurization and/or change in temperature.

Groundwater samples will be collected for trace metals analysis at a subset of sites where they can be obtained in a manner that minimizes contamination from groundwater sampling equipment and/or well construction. Trace metals samples will be collected with a Grunfos Redi-Flo 2 stainless steel variable frequency drive pump, or a Proactive Mini-Monsoon pump. The pumps will be field disassembled and washed in a Citranox solution between sampling events and attached to acid-rinsed Teflon-lined polyethylene tubing in the field. Equipment blanks will be collected each sampling run to document the contribution of metal sampling components to dissolved and total trace metals concentrations. Samples will be collected from the discharge end of the sample pump hose using standard trace metals clean hands / dirty hands standard operating procedures and containerized into laboratory-certified acid-washed bottles (Virginia Department of Environmental Quality, 2009). Bottles will be double-bagged and placed in coolers for overnight transport to Virginia's Division of Consolidated Laboratory Services in Richmond.

Quality Assurance and Quality Control

The quality of groundwater sampling procedures will be maintained by following established collection protocols described in the Standard Operating Procedures Manual for the Department of Environmental Quality (Virginia Department of Environmental Quality, 2009). All meters and probes used to collect field parameters will be calibrated against standardized solutions directly before sample collection. For field parameters to be considered valid, probes must check within acceptable limits at the end of each test (+/- 10% Specific Conductance, <0.5 mg/L Dissolved Oxygen, +/- 0.2 SU for pH). Temperature probes will be tested annually against a NIST certified thermometer at three reference points with an acceptable error of +/- 0.5° of the NIST reference thermometer.

Periodic equipment blanks will be collected to verify the efficacy of cleaning procedures and reduce the chances of carryover contamination between sampling sites. One major-ion / physical parameter equipment blank will be obtained for every 25 field samples collected. Major-ion / physical parameter equipment blanks will be collected after purging 5 volumes (of pump and tubing) with trace element grade deionized water. Two trace metals equipment blanks will be collected at the beginning of each sampling run to confirm the purity of post-discharge sample processing equipment, and to document any trace metal contamination from the dedicated submersible sampling pumps and tubing.

Cation – anion charge balance error will be used to evaluate the quality of groundwater samples collected. Cation – anion charge balance is a well-known and widely practiced approach for water sampling quality control (Murray and Wade, 1996). The anion and cation sums, when expressed as milli-equivalents per liter must balance because all potable waters are neutral (Greenberg et al., 1992). Groundwater quality samples with >10% charge balance error will be flagged as poor quality and not included for analysis. The equation used to determine charge balance error is:

$$\%\ Charge\ Balance\ Error = \frac{(\sum_{Cations} - \sum_{anions})}{(\sum_{Cations} + \sum_{anions})} \times 100$$

Data Management

Groundwater quality data obtained by DEQ are managed in several databases that, respectively, house field-collected and reported data. Groundwater sample data resulting from ambient groundwater sampling efforts by DEQ staff are stored in the Virginia Comprehensive Environmental Data System (CEDS). Data will be periodically migrated from the CEDS repository and uploaded to the DEQ Groundwater Geochemical Database of Virginia so that the data may be analyzed in a GIS environment and exported into more user friendly formats for data analysis and reporting. Water-chemistry data collected by GWCP staff will also be entered into the PostgreSQL database system for storage and retrieval for water supply planning purposes. PostgreSQL is used in conjunction with the Drupal content management system by DEQ for gathering and transforming data for water supply planning and water supply modeling efforts. Reported groundwater use and groundwater quality data associated with DEQ water withdrawal permit requirements will continue to be stored electronically in the Groundwater Permit (GWPERMIT) database.

Conclusions and Network Design Recommendations

The following sections detail the proposed placement and type of sampling locations for the delineation of ambient groundwater quality throughout Virginia - an area that spans 42,774 square miles, 48 major river basins, and hundreds of different rock types and unconsolidated sediments in six distinct geologic provinces.

Fractured-Rock Aquifers

Trend Well Monitoring

Analysis of available archival groundwater-quality data in the fractured-rock provinces of Virginia indicates that most groundwater data are not stable and change significantly through time. To accurately characterize potential trends and sources of natural variability in the groundwater geochemistry of fractured rock aquifers, long-term trend monitoring of dedicated observation wells is warranted.

Recommendations for the number and distribution of trend wells in the fractured-rock aquifers of Virginia will be directed by the distribution of geochemical rock types at the watershed scale. Trend sites will be targeted where geochemical rock type percentages exceed 15% of the total area of a watershed. Table 5 lists the watersheds, watershed identification numbers, drainage areas, percentages of geochemical rock types by watershed, and number of proposed trend-monitoring wells by watershed for the portion of the state where groundwater is obtained from fractured-rock aquifers. The map in figure 1 shows the distribution of geochemical rock-type groupings in each watershed west of the Coastal Plain. A network of 69 trend wells distributed among 30 watersheds is recommended in the portion of Virginia where groundwater is obtained from fractured-rock aquifers.

In order to account for potential complications associated with seasonality in the trend analysis, initial sampling of designated trend wells will occur monthly for a period of two years. If, during this time seasonal variations in groundwater chemistry are observed at the designated trend well, monthly sampling will continue for the duration of the monitoring effort. Where no seasonal component to groundwater geochemical concentrations can be discerned, sampling frequency on the designated trend well may be reduced. Semi-annual groundwater sampling has been shown to effectively provide data for the geochemical trend analysis of data from carbonate, crystalline, and siliciclastic rock aquifers of southeastern Pennsylvania (Reese and Lee, 1999) and may be a practical minimal sampling frequency for trend wells with no apparent seasonal component. Once sufficient data are obtained from designated trend wells, geochemical constituents will be analyzed for trend using either the Mann-Kendall trend or the Mann-Kendall seasonal trend tests as described in the Statistical Analysis of Groundwater Monitoring Data at RCRA Facilities Unified Guidance (U.S. Environmental Protection Agency, 2009).

Table 5: Watershed IDs for watersheds shown in figure 1; watershed drainage areas, percent coverage of watershed by geochemical rock type, and number of proposed trend wells by watershed. UC=undifferentiated crystalline rock; WPM=Western Piedmont metasedimentary rock; CMV= Chopawamsic metavocanic rocks; CSB= Carolina Slate Belt; MB= Mesozoic basins; COCarb=Cambrian-Ordovician Carbonates; DM Carb= Devonian-Mississippian Carbonates; CClast=Cambrian Clastics; DMClast = Devonian-Mississippian Clastics; SOClast= Silurian-Ordovician Clastics; PClast= Pennsylvanian Clastics

Watershed ID	Drainage Area, square miles	Percent Coverage by Geochemical Rock Type	Number of Proposed Trend Wells
30	1491	UC, 75%; WPM,4%; CMV,8%; CSB,4%;MB,9%	1
46	602	UC, 40%; WPM, 30%;CMV, 14%;MB, 16%	3
48	1251	COCarb, 19%; CClast, 21%; DMClast, 9%; SOClast24%; Pclast, 27%	4
50	532	UC, 75%; CMV,3%; CSB,21%;MB,1%	2
49	1140	UC, 54%; WPM,38%; CMV,4%; MB, 4%	2
51	692	CClast, 9%; COCarb,18%; DMCarb, 14%; DMClast, 27%; SOClast,32%	4
52	603	CClast, 7%; COCarb, 43%; DMClast, 7%; SOClast, 11%; UC,32%	2
27	1973	UC, 71%; WPM, 21%; CMV, 4%; MB, 2%; O, 2%	2
26	929	UC, 71%; CMV, 19%; MB, 9%; O, 1%	2
22	2112	CClast, 1%; COCarb, 10%; DMCarb, 18%; DMClast, 47%; SOClast,20%; UC, 4%	3
45	843	Pclast, 99%; O, 1%	1
23	826	COCarb, 40%; DMCarb, 7%; DMClast, 28%; SOClast, 15%; UC, 10%	2
41	848	UC, 53%; CSB, 46%; O, 1%	2
36	870	COCarb, 19%; DMClast 40%; SOClast, 40%; PClast, 1%	2
43	2152	CClast, 9%; COCarb, 18%; DMClast, 9%; SOClast; 2%; UC, 62%	1
37	792	UC, 71%; CSB, 28%; O, 1%	2
1	333	COCarb, 29%; DMClast, 50%; SOClast, 21%	2
20	981	UC, 53%; WP, 23%; CMV, 21%; MB, 3%	3
7	717	UC, 14%; WP, 21%; CMV, 11%; MB, 54%	2
4	755	UC, 61%; WP, 12%; MB, 27%	2
12	156	UC, 15%; WP, 61%; CMV, 24%;	3
54	538	COCarb, 37%; DMClast, 12%; SOClast, 18%; PClast, 33%	3
13	1562	UC, 73%; CMV, 12%; MB, 15%;	2
21	767	UC, 79%; WP, 19%; CMV, 2%	2
39	1458	UC, 39%; WP, 18%; CMV, 13%; CSB, 26%; MB, 4%	3
35	2148	CClast, 7%; COCarb, 6%; DMClast, 5%; SOClast, 2%; UC, 80%	1
47	338	UC, 72%; WP,28%	2
6	248	COCarb, 57; SOClast, 14%; UC, 29%	2
9	998	COCarb, 37%; DMClast, 39%; SOClast, 24%	3
11	1658	COCarb, 47%; DMClast, 15%; SOClast, 17%; UC, 21%	4

Prior to the initiation of trend well sampling, potential trend wells will be evaluated for radiologicals, clean metals, and the presence of anthropogenic contaminants by sampling for the presence of volatile organic compounds (VOCs) pursuant to the Environmental Protection Agency (EPA) National Environmental Methods Index (NEMI) 524.2., and the presence of Diesel Range Organics (DRO) pursuant to EPA NEMI 8015C. In cases where potential trend wells are regulated by the Virginia Department of Health (i.e. public water supply wells), initial raw water test data obtained by VDH will be evaluated for the presence of anthropogenic contaminants. Point source contamination of groundwater could trigger the detection of trends associated with point source pollution which are outside the scope of the proposed trend monitoring strategy. The presence of anthropogenic contaminants at a potential trend well site above minimum contamination levels will likely invalidate a well for trend well monitoring.

Spot Sampling

A portion of the groundwater sampling budget will be directed toward prioritized spot sampling to improve the coverage of groundwater geochemical data in areas where data are sparse or nonexistent, and toward investigating areas of special concern. Spot sampling will entail gathering geochemical parameters pertaining to major ions, nutrients, trace metals, radiologicals, and measurable physical parameters of sampled groundwater, and will be taken from existing wells where construction and basic hydrogeologic characteristics have been documented. Priority will be given to areas with the lowest or non-existent sample densities with the objective of improving sample resolution to at least 1 sample per 100 mi^2 in hard rock portions of the state (Figure 8). As densities resolve to the target value, new areas will be selected for sampling with refined density goals.

Special Projects

Agency directed investigations involving groundwater sampling and monitoring are anticipated intermittently. Project specific sampling strategies will be created for special studies on an as needed basis.

Coastal Plain

Recognizing that saltwater intrusion represents the second greatest threat to the Virginia Coastal Plain aquifers only after depletion of the resource, preference will be given to monitoring for this occurrence. An ambient groundwater quality monitoring well network in the Virginia Coastal Plain will utilize trend wells to target chloride/TDS concentrations, and spot well samples to characterize baseline water chemistry.

Chloride Trend Monitoring

McFarland (2010) points out the inadequacies in the current chloride monitoring network and recommends the network be redesigned based on a detailed hydrologic analysis. McFarland (2010) also states that the majority of the wells included in the current chloride network were not constructed solely for intrusion monitoring and many contain multiple screens making them unsuitable for chloride monitoring. A properly designed monitoring network on the mainland Coastal Plain would entail identifying multiple, complexly distributed areas of potential intrusion with the objective of determining locations at which observation wells would most likely intercept intrusion. The geology and structures associated with the Chesapeake Bay Impact Crater have created an extremely complex saltwater transition zone resulting in highly variable chloride concentration distributions at the local scale. Effective chloride monitoring will have to be scaled accordingly, very likely focused on individual major groundwater withdrawal facilities.

It is recommended that funding be allocated for a complete redesign of a chloride monitoring network based on a detailed hydrogeologic analysis to provide observation well locations, screen intervals, and sampling frequencies on the mainland Coastal Plain. Additionally, funding is needed to revise the hydrogeologic framework on the Eastern Shore to include a more detailed characterization of paleochannels. The effort should recommend the number, location, and screen intervals of monitoring wells needed to characterize chloride concentrations in and adjacent to the paleochannels. A large scale drilling program would then be needed for construction of the observation wells recommended by these efforts.

Sampling from the current chloride monitoring network will need to occur in order to monitor chloride trends during the network redesign process. In an effort to expand the number of chloride monitoring wells available for sampling in the interim chloride monitoring network, a review of historic chloride sample data was conducted to select wells for interim chloride monitoring that would yield representative samples and focus sampling efforts in areas where chloride concentrations are increasing. This review utilized historic chloride monitoring data from 556 wells in the Virginia Coastal Plain and Eastern Shore (McFarland, 2010) and resulted in the designation of 10 additional monitoring wells as potential interim chloride monitoring well candidates. An additional 3 wells may be incorporated into the interim network pending verification of well construction details. New well designations were assigned from an initial pool of 75 potential monitoring wells that were shown to exhibit overall historic increases in chloride concentration from below 250 mg/L to above 250 mg/L (Tier 1 Wells), or historic chloride concentration increases of an additional 250 mg/L over an initial chloride concentration equal to or above 250 mg/L (Tier 2 Wells). Figure 1 in Appendix B illustrates the locations of these 75 wells and Tables 1 and 2 of Appendix B lists the site names, locations, and range in chloride concentrations for the listed wells. Tables 3 and 4 in Appendix B summarize evaluation of the Mainland Coastal Plain and Eastern Shore Tier 1 and Tier 2 wells for inclusion in the interim chloride monitoring network. A total of 19 wells were identified as either Tier 1 or Tier 2 that were deemed suitable for sampling. Six of these wells are in the existing chloride monitoring network. A total of 56 wells were eliminated as candidates from the potential interim sample network due to potential complications associated with well construction, well placement, well abandonment, or erroneous sample data.

The interim chloride monitoring network will be comprised of the 130 wells in the existing chloride monitoring network, the 10 out of network wells evaluated as Tier 1 or Tier 2, three wells with pending construction documentation for final evaluation as Tier 1 and Tier 2, and a newly identified and as yet un-sampled well (selected on the basis of its proximity to increasing chloride concentrations, construction, and availability for sampling) for a potential total pool of 144 wells. Sampling efforts for the interim chloride monitoring network should consist of quarterly sampling of all remaining Tier 1 and Tier 2 wells, the newly identified and as yet un-sampled well, and the three wells still awaiting construction documentation for final evaluation as Tier 1 and Tier 2, for a potential total of 20 wells. Quarterly sampling should be conducted instead of continuing with the current practice of obtaining a single sample from a limited number of wells on an informal, periodic, multi-year rotational basis. Quarterly sampling will facilitate distinguishing short-term chloride fluctuations due to localized upconing from long-term increases more likely to be indicative of lateral salt water intrusion. Table 6 lists the Tier 1 and Tier 2 wells approved as additions to the current chloride monitoring network and the wells needing additional construction information before final evaluation. Table 7 lists all the wells comprising the proposed interim chloride monitoring network compiled from the existing network, the additional Tier 1 and Tier 2 wells, and the newly identified and currently unsampled well (well 57F 36). Figure 10 illustrates the general location of the wells in the proposed interim chloride monitoring network and those proposed for sampling.

Table 6: Tier 1 and Tier 2 Wells approved as additions to the current chloride monitoring network.

USGS Local #	Well or Owner Name	DEQ #	EVALUATION REMARKS
Mainland Tier 1 Wells			
56H 25	Diascund SOW 177A	147-0169	REMAIN Tier 1
52N 25	Fort AP Hill Picnic Area	116-0383	REMAIN Tier 1
62B 1	Pungo SOW 98A	228-0167	REMAIN - disregarding extremely low initial sample **drops well to Tier 2 below**
60C 40	City of Chesapeake TW-1	234-0174	Additional well construction data needed for evaluation - very likely multi screened
60C 58	National Linen Service Well 1	220-0049	Additional info needed - listed as multi-screened well 655-665 and 665-695
Mainland Tier 2 Wells			
61B 12	Fentress SOW 91E	234-0191	REMAIN Tier 2
61D 5	Ferry Road SOW 155	228-0162	REMAIN Tier 2
62B 2	Pungo SOW 98B	228-0168	REMAIN Tier 2
58F 50	Newport News Park SOW 171A	216-0018	REMAIN Tier 2 (well condition currently under evaluation via packer test)
62B 1	Pungo SOW 98A	228-0167	REMAIN but becomes Tier 2 - disregarding extremely low initial sample drops well to **Tier 2**
61B 13	Fentress SOW 91F	234-0192	REMAIN Tier 2
61A 5	City of Chesapeake TW-2	234-0175	Additional well construction data needed for evaluation - very likely multi screened
Eastern Shore Tier 1 Wells			
65M 3	HV Drewer and Son #1	100-0237	REMAIN Tier 1
62G 29	Bayshore Well 7	165-0389	REMAIN Tier 1
62G 16	Bayshore #2 Gate	165-0110	REMAIN Tier 1
62G 30	Cape Charles Tower Well	165-0387	REMAIN Tier 1
62G 34	Cherrystone Campground Well 8	165-0096	REMAIN Tier 1
Eastern Shore Tier 2 Wells			
66M 25	Jenkins Bridge SOW 181C	100-0563	REMAIN Tier 2
66M 23	Jenkins Bridge SOW 181A	100-0561	REMAIN Tier 2
66M 26	Jenkins Bridge SOW 181D	100-0564	REMAIN Tier 2

Table 7: Proposed Interim Chloride Monitoring Well Network.
Wells highlighted in gray are proposed interim Chloride sampling wells.

LOCAL	LAT	LON	SOW_ID	OTHERID	NAME	LOCAL	LAT	LON	SOW_ID	OTHERID	NAME
52B 10	36.65444444	-77.33611111	SOW 178C	187-00182	Little Texas Res St	58C 59	36.85916667	-76.5866667	SOW 141C	161-00363	Chuckatuck
52B 11	36.65444444	-77.33611111	SOW 178D	187-00183	Little Texas Res St	58D 12	36.96527778	-76.5152778			James River Bridge
52B 12	36.65444444	-77.33611111	SOW 178E	187-00184	Little Texas Res St	58F 1	37.17416667	-76.5655556	SOW 002	216-00002	Lee Hall Reservoir
52N 25	38.084722	-77.329167		116-383	Fort AP Hill Picnic Area	58F 7	37.15222222	-76.5763889		216-00004	Fort Eustis PW-3
53J 24	37.55449167	-77.21471667	SOW 234-A	163-230	Bottoms Bridge Peace Road Res St	58F 50	37.20222222	-76.5697222	SOW 171A	216-00018	Newport News Res St
53J 25	37.55449167	-77.21471667	SOW 234-B	163-231	Bottoms Bridge Peace Road Res St	58F 51	37.20222222	-76.5697222	SOW 171B	216-00019	Newport News Res St
54C 10	36.77870278	-77.071325	SOW 221A	187-00242	Sebrell	58F 52	37.20222222	-76.5697222	SOW 171C	216-00020	Newport News Res St
54C 11	36.77871944	-77.07135	SOW 221B	187-00243	Sebrell	58F 53	37.20222222	-76.5697222	SOW 171D	216-00021	Newport News Res St
54C 12	36.77871667	-77.07138056	SOW 221C	187-00244	Sebrell	58F 81	37.16694444	-76.5544444		216-00047	NN BGD LH3-8 Lower Potomac Mon
54C 13	36.77873056	-77.071475	SOW 221D	187-00245	Sebrell	58F 82	37.19138889	-76.5105556		199-00107	NN BGD LH3-7 Middle Potomac Mon
54P 3	38.169422	-77.038136		196-00133	Oak Grove	58F 89	37.17833333	-76.5883333		216-00040	NN BGD LH-1 Middle Potomac Prod
55A 3	36.60888889	-76.96694444	SOW 086	187-00146	Nottoway River	58F 92	37.178525	-76.587975		216-00053	NN BGD LH-1 Upper Potomac Mon
55B 65	36.67583333	-76.94055556	SOW 145B	233-00011	P.D. Camp Comm. Coll.	58F 93	37.17783333	-76.5878861		216-00054	NN BGD LH-1 Middle Potomac Mon
55B 67	36.67583333	-76.94055556	SOW 145D	233-00013	P.D. Camp Comm. Coll.	58F127	37.19708611	-76.5927778	SOW 195	147-00259	Greenmont Prod. Well
55E 7	37.01463611	-76.89419167	SOW 214A	190-00111	Ellis Fork Res St	58H 2	37.41611111	-76.5372222		136-00027	Gloucester Co. Well #1 (Belroi)
55E 8	37.01463056	-76.89414167	SOW 214B	190-00112	Ellis Fork Res St	58H 6	37.39194444	-76.5238889	SOW 168A	136-00121	Gloucester Landfill
55E 9	37.01462222	-76.894075	SOW 214C	190-00113	Ellis Fork Res St	58H 10	37.43836944	-76.5481083		136-00144	Gloucester BGD Prod. #1
55H 23	37.42638889	-76.97027778	SOW 233A	163-223	Windsor Shades Res St	58H 11	37.43161944	-76.5477917		136-00145	Gloucester BGD Prod. #2
55H 24	37.42638889	-76.97027778	SOW 233B	163-224	Windsor Shades Res St	58J 1	37.60555556	-76.595		159-00012	Town of Saluda Old Well
55H 25	37.42638889	-76.97027778	SOW 233C	163-225	Windsor Shades Res St	59D 25	36.96543056	-76.4200361	SOW 213	216-00086	Dominion Terminal Associates
55H 26	37.42638889	-76.97027778	SOW 233D	163-226	Windsor Shades Res St	59F 1	37.21777778	-76.4886111	SOW 027	199-00027	Yorktown
55H 27	37.42638889	-76.97027778	SOW 233E	163-227	Windsor Shades Res St	59H 4	37.44450556	-76.3984333	SOW 193A	157-00042	North
55H 28	37.42638889	-76.97027778	SOW 233F	163-228	Windsor Shades Res St	59H 6	37.44454722	-76.3982889	SOW 193C	157-00044	North
55J 15	37.58988611	-76.87651111		150-00145	Mann Tract MW-1	59J 6	37.53361111	-76.4366667		159-00014	Piankatank Conference Ctr.
55J 16	37.58972222	-76.87611111		150-00146	Mann Tract MW-2	59K 1	37.71361111	-76.3836111	SOW 015	151-00015	Kilmarnock
55J 17	37.58972222	-76.87611111		150-00147	Mann Tract MW-3	59K 17	37.66175	-76.4299111		151-00050	West Irvington Well #2
55J 18	37.58972222	-76.87611111		150-00148	Mann Tract MW-4	59K 21	37.71222222	-76.3788889		151-00001	Well 2
55J 19	37.58972222	-76.87611111		150-00149	Mann Tract MW-5	60B 3	36.64333333	-76.3380556	SOW 090A	234-00134	Fennema
56A 10	36.5625	-76.78388889	SOW 088A	161-00349	Somerton Swamp	60B 4	36.64333333	-76.3380556	SOW 090B	234-00135	Fennema
56A 12	36.5625	-76.78388889	SOW 088B	161-00351	Somerton Swamp	60C 6	36.81472222	-76.2858333		234-00014	Lone Star (LaFarge) Cement Corp
56F 19	37.24638889	-76.77638889		147-00120	JCCSA-St. George's Hund.	60C 7	36.85429444	-76.3209	SOW 194	220-00004	Pinner's Point WTP
56F 52	37.24828056	-76.76845556		147-00285	JCSA-BGD-1C,Obs.	60C 40	36.783444	-76.372222		234-00174	City of Chesapeake TW-1
56F 53	37.24812222	-76.76879167		147-00286	JCSA-BGD-1A,Obs.	60C 41	36.77083333	-76.3058333	SOW 164	234-00165	VEPCO
56F 54	37.24833056	-76.76923333		147-00287	JCSA-BGD-1, Prod.	60C 58	36.797778	-76.351667		220-00049	National Linen Service Well 1
56F 55	37.24842778	-76.76877222		147-00288	JCSA-BGD-1B, Obs.	60L 28	37.87027778	-76.3175	SOW 216A	166-00114	Surprise Hill Research Station
56F 56	37.24798056	-76.76869167		147-00294	JCSA-BGD-2, Prod.	60L 29	37.87027778	-76.3175	SOW 216B	166-00115	Surprise Hill Research Station
56F 57	37.24692222	-76.76849722		147-00302	JCSA-BGD-3, MP-2	60L 30	37.87027778	-76.3175	SOW 216C	166-00116	Surprise Hill Research Station
56F 59	37.24711944	-76.76801111		147-00304	JCSA-BGD-5, LP-3	60L 31	37.87027778	-76.3175	SOW 216D	166-00117	Surprise Hill Research Station
56F 60	37.24650556	-76.76938056		147-00308	JCSA-BGD-6 , LP-2	60L 32	37.87027778	-76.3175	SOW 216E	166-00118	Surprise Hill Research Station
56G 13	37.25944444	-76.75027778		147-00038	Indigo Park	60L 33	37.87027778	-76.3175	SOW 216F	166-00119	Surprise Hill Research Station
56H 25	37.41416667	-76.85916667	SOW 177A	147-00169	Diascund Res Stat	60L 34	37.87027778	-76.3175	SOW 216G	166-00120	Surprise Hill Research Station
56H 26	37.41416667	-76.85916667	SOW 177B	147-00170	Diascund Res Stat	60L 35	37.87027778	-76.3175	SOW 216H	166-00121	Surprise Hill Research Station
56H 27	37.41416667	-76.85916667	SOW 177C	147-00171	Diascund Res Stat	60L 36	37.87027778	-76.3175	SOW 216J	166-00122	Surprise Hill Research Station
56H 28	37.41416667	-76.85916667	SOW 177D	147-00172	Diascund Res Stat	61A 5	36.593	-76.209917		234-00175	City of Chesapeake TW-2
56H 29	37.41416667	-76.85916667	SOW 177E	147-00173	Diascund Res Stat	61A 15	36.59266111	-76.2101694		234-00217	NWR OW-1 (Chesapeake)
56H 40	37.38694444	-76.80166667		147-00268	JCCSA W-1#2c	61A 16	36.59274722	-76.2102139		234-00218	NWR OW-2 (Chesapeake)
56J 11	37.52388889	-76.76138889	SOW 073	149-00004	West Point Airport	61A 17	36.59293056	-76.2103056		234-00219	NWR OW-3 (Chesapeake)
56J 13	37.55472222	-76.81777778		150-00087	Magnolia North	61A 18	36.59159167	-76.2113889		234-00225	NWR OW-4 (Chesapeake)
57C 21	36.78416667	-76.64361111	SOW 099A	161-00359	Prudden	61A 19	36.59083333	-76.1888889		234-00226	NWR OW-5 (Chesapeake)
57C 22	36.78416667	-76.64361111	SOW 099B	161-00357	Prudden	61B 5	36.7075	-76.1297222	SOW 091B	234-00065	Fentress
57C 23	36.78416667	-76.64361111	SOW 099C	161-00358	Prudden	61B 6	36.7075	-76.1297222	SOW 091C	234-00066	Fentress
57E 10	37.04333333	-76.71638889	SOW 144B	146-00244	Moonlight	61B 12	36.7075	-76.1297222	SOW 091E	234-00191	Fentress
57E 14	37.04805556	-76.72	SOW 144A	146-00243	Moonlight	61B 13	36.7075	-76.1297222	SOW 091F	234-00192	Fentress
57F 16	37.19222222	-76.68194444	SOW 087A	190-00067	Hog Island	61B 14	36.7075	-76.1297222	SOW 091G	234-00193	Fentress
57F 24	37.19222222	-76.68194444	SOW 087B	190-00078	Hog Island	61B 15	36.7075	-76.1297222	SOW 091H	234-00194	Fentress
57F 36	37.23190214	-76.6477918		147-00309	Busch Gardens Flume Obs Well	61B 16	36.7075	-76.1297222	SOW 091J	234-00195	Fentress
57G 22	37.32611111	-76.73722222		147-00023	Old Stage Manor	61C 1	36.87305556	-76.2058333		217-00006	Moores Bridge Test Well
57G 24	37.27444444	-76.69583333		147-00098	Colonial Williamsburg F	61D 5	36.90694444	-76.1805556	SOW 155	228-00162	Ferry Road
57H 10	37.38583333	-76.70138889		147-00139	York River State Park #3	62B 1	36.690556	-76.009722	SOW 98A	228-00167	Pungo
57H 20	37.43916667	-76.67833333	SOW 192A	136-00140	West End Site MW-1	62 B 2	36.690556	-76.009722	SOW 98B	228-00168	Pungo
57H 21	37.43916667	-76.67833333	SOW 192B	136-00141	West End Site MW-2	62G 16	37.262083	-76.021861		165-00110	Bayshore #2 Gate
57H 22	37.43916667	-76.67833333	SOW 192C	136-00142	West End Site MW-3	62G 24	37.259075	-76.0183528			Sustainable Park Observation Well #1
57J 3	37.50222222	-76.71555556	SOW 074	149-00005	Gressitt	62G 25	37.259075	-76.0183528			Sustainable Park Observation Well #2
58A 77	36.61527778	-76.55555556	SOW 180A	161-00412	Dismal Swamp Res St	62G 29	37.26225	-76.021083		165-00389	Bayshore well 7
58A 78	36.61527778	-76.55555556	SOW 180B	161-00413	Dismal Swamp Res St	62G 30	37.268361	-76.004861		165-00387	Cape Charles Tower Well
58A 79	36.61527778	-76.55555556	SOW 180C	161-00414	Dismal Swamp Res St	62G 34	37.290722	-76.012944		165-00096	Cherrystone Campground Well 8
58A 80	36.61527778	-76.55555556	SOW 180D	161-00415	Dismal Swamp Res St	63F 52	37.13527778	-75.9522222	SOW 182B	165-00263	Kiptopeke
58A 81	36.61527778	-76.55555556	SOW 180E	161-00416	Dismal Swamp Res St	65M 3	37.920222	-75.729917		100-00237	HV Drewer and Son #1
58B270	36.72166667	-76.61527778	SOW 169C	161-00392	Lake Kilby	66M 23	37.93611111	-75.605	SOW 181A	100-00561	Jenkins Bridge
58B271	36.72138889	-76.60972222	SOW 169D	161-00393	Lake Kilby	66M 24	37.93611111	-75.605	SOW 181B	100-00562	Jenkins Bridge
58B273	36.73	-76.60888889	SOW 169F	161-00395	Lake Kilby	66M 25	37.936111	-75.605	SOW 181C	100-00563	Jenkins Bridge
58C 58	36.85916667	-76.58666667	SOW 141B	161-00362	Chuckatuck	66M 26	37.936111	-75.605	SOW 181D	100-00564	Jenkins Bridge

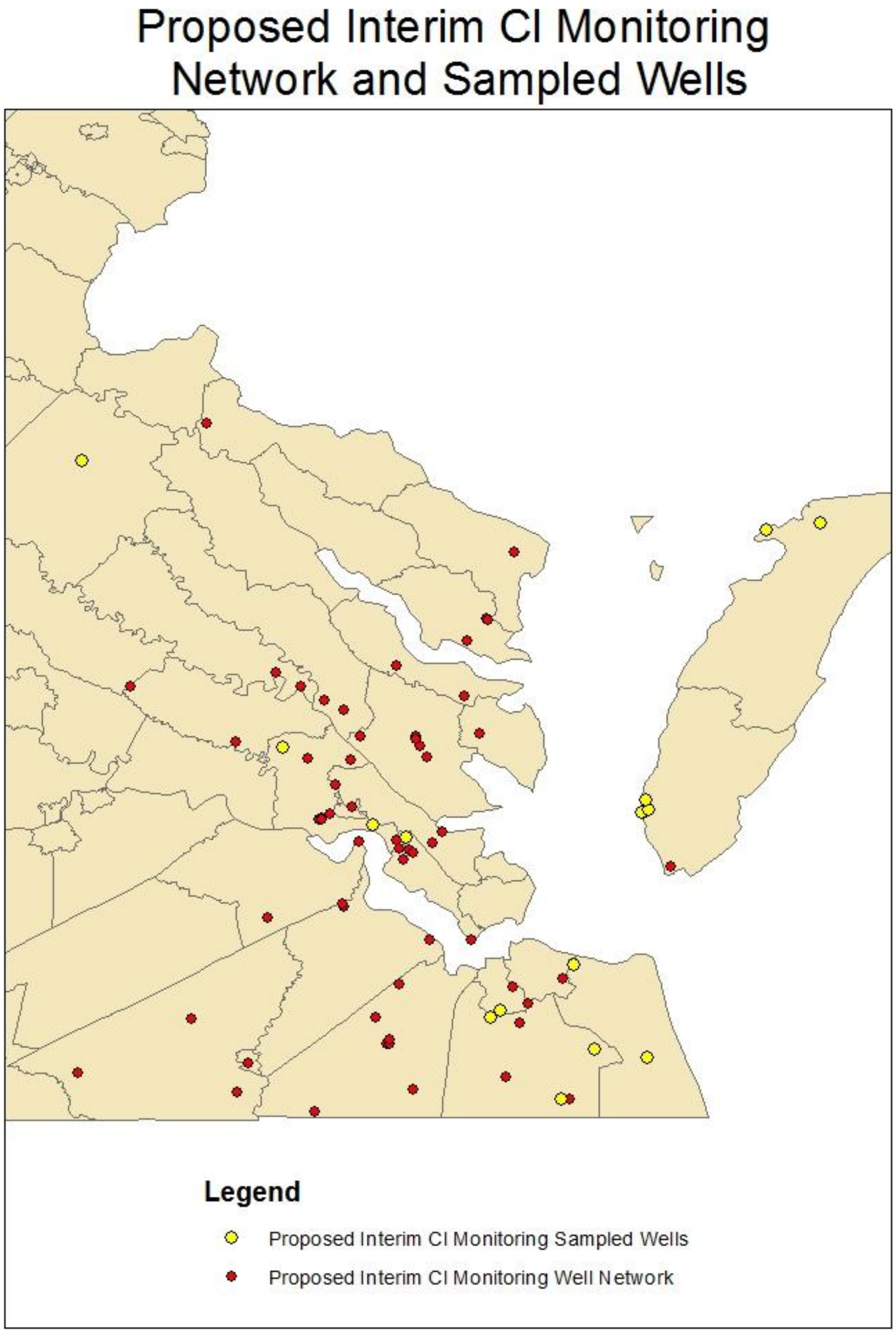


Figure 10: Locations of proposed Interim Chloride Monitoring Network wells and proposed sampling wells.

Spot Sampling

Groundwater quality data densities shown in Figure 8 imply that most of the Coastal Plain has better data coverage than in the fractured-rock aquifers, but the two dimensional figure does not adequately represent the vertical distribution of multiple confined aquifer systems at each location. Data density maps for individual aquifer systems in the Coastal Plain would certainly be much lower than the overall areal distribution depicted in Figure 8. A closer look at the Coastal Plain region as presented in Figure 11 shows several areas as large as 30 square miles that lack any useful water quality data at all. Areas in the Coastal Plain with the lowest or non-existent water quality data will be targeted through spot sampling with the objective of improving sample density to least 1 per 6 mi^2. As densities resolve to that target value, new areas will be selected for spot sampling with refined density goals. Spot sampling will entail gathering geochemical parameters pertaining to major ions, nutrients, trace metals, radiologicals, and measurable physical parameters of sampled groundwater. Wells screened in the unconfined surficial aquifer will also be evaluated for the presence of anthropogenic contaminants by sampling for the presence of volatile organic compounds (VOCs) pursuant to the Environmental Protection Agency (EPA) National Environmental Methods Index (NEMI) 524.2., and the presence of Diesel Range Organics (DRO) pursuant to EPA NEMI 8015C. Priority will be given to new wells added to the State Observation Well network under DEQ issued Ground Water Withdrawal Permit conditions and then to existing wells where construction and basic hydrogeologic characteristics have been sufficiently documented.

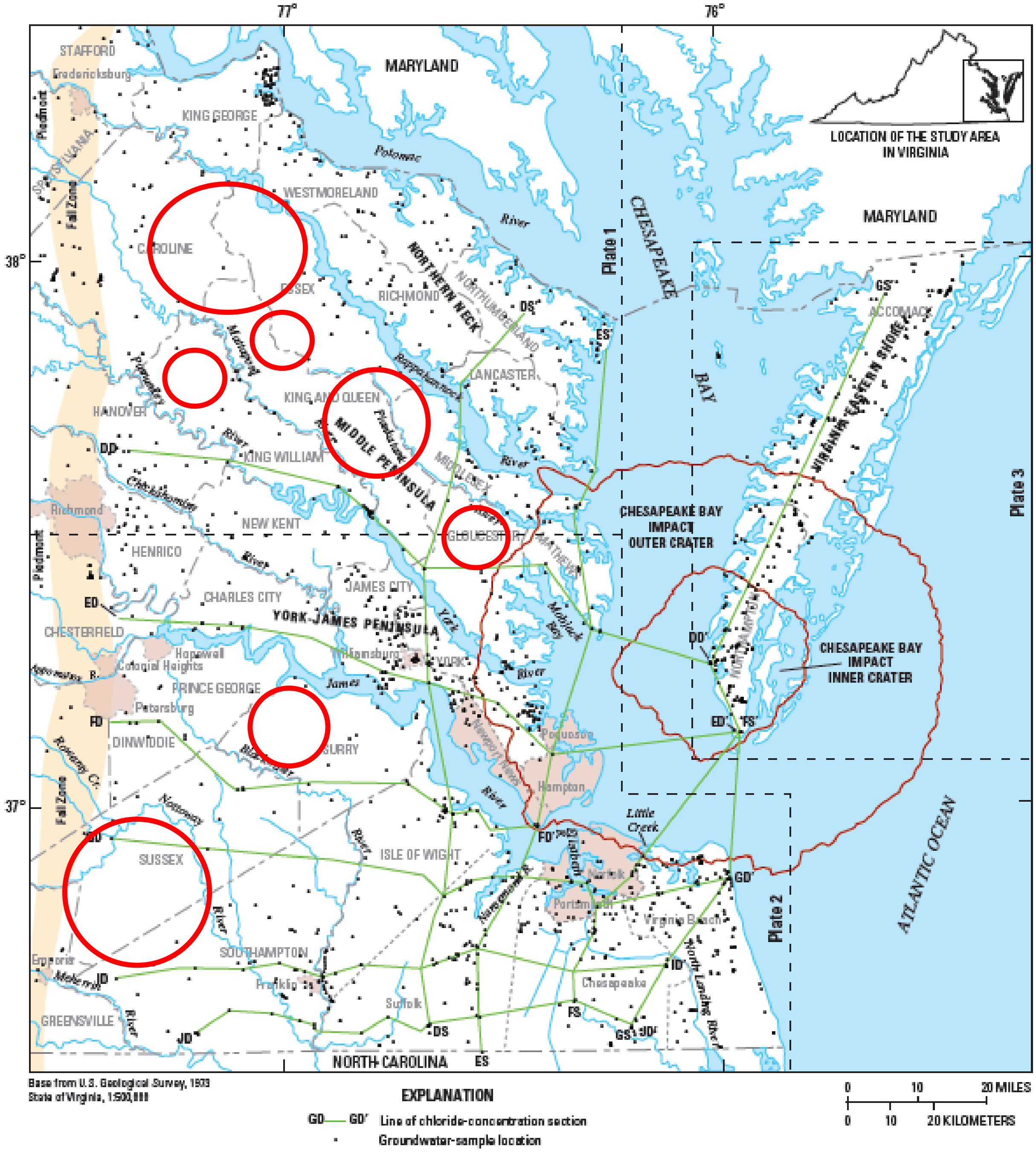


Figure 11: Distribution of groundwater sample locations for the Virginia Coastal Plain and Eastern Shore. Red circles highlight areas with little to no density of water quality data (Modified from McFarland 2010).

Special Projects

Agency directed investigations involving groundwater sampling and monitoring are anticipated intermittently. Project specific sampling strategies will be created for special studies on an as needed basis.

Programmatic Costs

Additional staff and equipment will be needed to implement the full sampling effort described in the strategy. A few basic assumptions regarding sampling rates and equipment requirements were made in order to derive programmatic cost estimates for ambient groundwater monitoring:

- 2 person teams will be required for sample collection.
- Each team will require a sample pump truck and pickup truck for sample collection and delivery.
- Each 2-person team can be expected to sample a total of 12 wells in a four week period, leaving 8 days in that time period for spot sampling, data management and analysis, administrative duties, special projects, or report preparation.

Fuel costs and per-diem are substantial line items in the annual expenditure since much of the sampling will be organized into week-long "sample runs" that will frequently require considerable driving and over-night lodging. The majority of annual sampling is expected to consist of one analyte schedule that includes basic physical water quality parameters and major ions. Additional analyte schedules will be run for trace metals and radiologicals at spot sample sites. New sample schedules may need to be created for special project sampling events. An additional set of costs associated with program start up will be incurred during the first years of program operation. These costs include additional vehicles, field equipment, and lab costs for the analysis of trace metals, radiologicals, and anthropogenic contaminants at new trend well sites.

The cost analysis assumes a monthly sampling frequency for all 69 wells in the fractured-rock portion of the trend well monitoring network, and 20 annual spot samples taken throughout the year. This equates to 848 sampling events annually. Based on the stated assumptions, a total of 14 employees (7 teams of 2 personnel) will be required to complete all annual sampling. Table 8a summarizes annual and start-up programmatic cost estimates for the ambient groundwater monitoring strategy in the fractured rock portion of Virginia.

Table 8a: Estimated costs for full implementation of groundwater monitoring strategy in fractured rock regions of Virginia. *36 = number of week long sample runs required to obtain all trend well samples. Fuel costs based on 200 mi. days at $4.00/gal. PerDiem/Lodging estimated using current state allowances.

Estimated Costs for Full Implementation of Groundwater Monitoring Strategy in Fractured Rock Regions of Virginia			
ITEM	NUMBER	ITEM COST	TOTAL
ANNUAL OPERATING COSTS			
Full Time Employee - Salary & Benefits	14	$80,100	$1,121,400
Per Diem/Lodging*	36	$3,016	$108,576
Fuel*	36	$3,570	$128,520
Equipment Mainenance / Replacement			$25,000
LABORATORY ANALYTICAL COSTS			
Trend Sites			
CORE sample	828	$235	$194,580
Equipment Blank	14	$235	$3,290
Spot Sites			
CORE sample	20	$235	$4,700
RADIOLOGICAL sample	20	$250	$5,000
CLEAN METALS sample	20	$260	$5,200
CLEAN METALS field blank	20	$260	$5,200
INITIAL PROGRAM DEVELOPMENT COSTS			
Sample Trucks	7	$50,000	$350,000
Pickup Trucks	7	$25,000	$175,000
Anthropogenic Sampling	69	$1,000	$69,000
RADIOLOGICAL sample	69	$250	$17,250
CLEAN METALS sample	69	$260	$17,940
CLEAN METALS field blank	69	$260	$17,940
Field Equipment	7	$3,000	$200,000
INITIAL PROGRAM DEVELOPMENT			$847,130
ANNUAL OPERATING AND ANALYTICAL			$1,596,266

The ambient groundwater monitoring strategy for the Coastal Plain of Virginia recommends a complete redesign of the chloride monitoring network based on a detailed hydrologic analysis. The hydrologic analysis should consider current ground water withdrawal amounts and locations on the chloride concentration sections defined by McFarland (2010) to predict the future movement of chloride and the proposed locations of wells to detect that anticipated movement. The costs for this analysis are unknown, as are future costs associated with the implementation of the redesigned chloride network (which are contingent on the findings of the hydrologic analysis).

An interim chloride monitoring effort will be required while complete redesign of the chloride monitoring network is underway. This strategy proposes obtaining quarterly samples from the sixteen wells successfully evaluated as Tier 1 and Tier 2, plus the newly identified and as yet un-sampled well 57F 36, and three wells awaiting final verification as Tier 1 and Tier 2. Under this description, potentially a total of 20 wells will be sampled quarterly for a total of 100 sampling events annually. Based on the assumptions and expectations described in the beginning of the Programmatic Costs section, a total of 2 employees will be needed to fulfill the requirements described in the Coastal Plain portion of the ambient groundwater monitoring strategy. Table 8b summarizes the estimated annual and start-up program expenditures associated with quarterly sampling of the interim Coastal Plain ambient groundwater quality monitoring network.

Table 8b: Estimated costs for initial implementation of groundwater monitoring strategy in the Virginia Coastal Plain.

Estimated Costs for Full Implementation of Groundwater Monitoring Strategy in Coastal Plain Region of Virginia			
ITEM	**NUMBER**	**ITEM COST**	**TOTAL**
ANNUAL OPERATRING COSTS			
Full Time Employee - Salary & Benefits	4	$80,100	$320,400
Per Diem/Lodging	36	$1,508	$54,288
Fuel	36	$1,016	$36,590
Equipment Mainenance / Replacement			$12,500
LABORATORY ANALYTICAL COSTS			
Trend Sites			
CORE sample	300	$235	$194,580
Equipment Blanks	36	$235	$8,460
Spot Sites			
CORE sample	6	$235	$1,410
RADIOLOGICAL sample	6	$250	$1,500
CLEAN METALS sample	6	$260	$1,560
Anthropogenic Sampling	2	$1,000	$2,000
INITIAL PROGRAM DEVELOPMENT COSTS			
Sample Trucks	2	$50,000	$100,000
Pickup Trucks	2	$25,000	$50,000
Field Equipment			$100,000
INITIAL PROGRAM DEVELOPMENT			$250,000
ANNUAL OPERATING AND ANALYTICAL			$633,288

References

Back, W., 1966, Hydrochemical facies and ground-water flow patterns in northern part of Atlantic Coastal Plain: USGS Professional Paper 498-A, 42p.

Bailey, C.M., Berquist, P.J., Mager, S.M., Knight, B.D., Shotwell, N.L., and Gilmer, A.K., 2003, Bedrock Geology of the Madison Quadrangle, Virginia: Virginia Division of Mineral Resources Publication 157, 22 p.

Balk, R., 1937, Structural Behavior of Igneous Rocks: Geological Society of America Memoir 5, 177 p.

Barlow, P.M., 2003, Ground Water in Freshwater-Saltwater Environments of the Atlantic Coast: USGS Circular 1262, 124 p.

Boughton, C.J., and McCoy, K.J., 2006, Hydrogeology, Aquifer Geochemistry, and Ground-Water Quality in Morgan County, West Virginia: U.S. Geological Survey Scientific Investigations Report 2006-5198, 56 p.

Briel, L.I., 1997, Water Quality in the Appalachian Valley and Ridge, The Blue Ridge, and the Piedmont Physiographic Provinces, Eastern United States: United States Geological Survey Professional Paper 1422-D, 115 p.

Butts, C., 1940, Geology of the Appalachian Valley in Virginia: Virginia Geological Survey Bulletin 52, 568 p.

Cady, R.C., 1936, Ground-Water Resources of the Shenandoah Valley, Virginia: Virginia Geological Survey Bulletin 45, 137p.

Chapman, M.J., Bolich, R.E., and Huffman, B.A., 2005, Hydrogeologic setting, groundwater flow, and groundwater quality at the Lake Wheeler Road research station, 2001-03, North Carolina Piedmont and Mountains Resource Evaluation Program: U.S. Geological Survey Scientific Investigations Report 2005-5166, 85p.

Colman, S.M., Halka, J.P., C.H. Hobbs, I., Mixon, R.B., and Foster, D.S., 1990, Ancient channels of the Susquehanna River beneath the Chesapeake and Delmarva Peninsula: Geological Society of America Bulletin, 102: 1268-1279.

Drummond, D.D., and Bolton, D.W., 2010, Arsenic in Ground Water in the Coastal Plain Aquifers of Maryland: Maryland Department of Natural Resources, Maryland Geological Survey, Report of Investigations No. 78, 71 p.

Freeze, A.R., and Cherry, J.A., 1979, Groundwater, Prentice-Hall, Inc., 604 p.

Greenberg, A.E., Clesceri, L.S., and Eaton, A.D., 1992, Standard Methods for the Examination of Water and Wastewater: Washington, D.C., American Public Health Association, p. 1100.

Harlow, G.E., Jr., and Lecain, G.D., 1993, Hydraulic characteristics of, and ground water flow in, coal-bearing rocks of southwestern Virginia: U.S. Geological Survey Water Supply Paper 2388, 36p.

Harsh, J.F., and Laczniak, R.J., 1990, Conceptualization and analysis of ground-water flow system in the Coastal Plain of Virginia and adjacent parts of Maryland and North Carolina: USGS Professional Paper 1404-F, 100p.

Helsel, D.R., Mueller, D.K., and Slack, J.R., 2006, Computer Program for the Kendall Family of Trend Tests: U.S. Geological Survey Scientific Investigations Report 2005-5275, 4p.

Hem, J.D., 1992, Study and Interpretation of the Chemical Characteristics of Natural Water: United States Geological Survey Water Supply Paper 2254, 263 p.

Heywood, C.E., and Pope, J.P., 2009, Simulation of Groundwater Flow in the Coastal Plain Aquifer System of Virginia: USGS Scientific Investigations Report 2009-5039, 115p.

Hibbard, J.P., van Staal, C.R., Rankin, D.W., and Williams, H., 2006, Lithotectonic Map of the Appalachian Orogen, Canada-United States of America; Geological Survey of Canada, Map 2096A, scale: 1:1,500,000.

Hobbs, C., Powars, D., Lukenbach, M., and Berquist, R.C., 2011, Virginia's Eastern Shore: Barrier Islands to the Chesapeake Bay Impact Structure, 41st Virginia Geological Field Conference, October 29-30, 2011, 42 p.

Johnston, P.M., 1962, Geology and Ground-Water Resources of the Fairfax Quadrangle, Virginia: United States Geological Survey Water Supply Paper 1539-L, 61 p.

Kelly, W.R., and Meyer, S., 2005, Temporal Changes in Deep Bedrock Groundwater Quality in Northeastern Illinois: Illinois State Water Survey Center for Groundwater Science Contract Report 2005-05, 49 p.

Kendall, M.G., 1975, Rank Correlation Methods, 4th ed., Charles Griffin, London, 1975.

Krantz, D.E., Levin, D.R., and Wilkel, G.R., Unpublished data from a seismic survey conducted in May, 2005, http://www.eeescience.utoledo.edu/Faculty/Krantz/Va_Coast_figures/Fig14.Virginia_ES_paleochannels.jpg.

Lane, S.L., Flannagan, S., and Wilde, F.D., 2003, Selection of Equipment for water sampling (ver 2.0): U.S. Geological Survey Techniques of Water-Resources Investigations, Book 9, chap. A2.

Langmuir, D., 1997, Aqueous Environmental Geochemistry: Upper Saddle River, Prentice Hall, 600 p.

Mace, R.E., 2011, Peer Review of Virginia's Groundwater Management Program: Texas Water Development Board, 39 p.

Manda, A.K., Mabee, S.B., and Wise, D.U., 2008, Influence of Rock Fabric on Fracture Attribute Distribution and Implications for Groundwater Flow in the Nashoba Terrane, Eastern Massachusetts: Journal of Structural Geology, v. 30, p. 464-477.

Mann, H.B., 1945, Non-parametric test against trend, Econometrica, 13, 245-259, 1945.

McFarland, E.R., 2010, Groundwater-quality data and regional trends in the Virginia Coastal Plain, 1906-2007: U.S. Geological Survey Professional Paper1772, 86p., 14pls.

McFarland, E.R., and Bruce, T.S., 2006, The Virginia Coastal Plain hydrogeologic framework: U.S. Geological Survey Professional Paper 1731, 118p., 25 pls.

McLoughlin, T.F., 1986, Explanation of the regional tectonic map of the southwestern coal field of Virginia: U.S. Department of Labor, Mine Safety and Health Administration, Informational Report IR 1177, 17p.

Meinzer, O.E., 1923, The Occurrence of Ground Water in the United States With a Discussion of Principles: United States Geological Survey Water Supply Paper 489, 321 p.

Miller, M.S., 1974, Stratigraphy and coal beds of upper Mississippian and lower Pennsylvanian rocks in southwest Virginia: Virginia Division of Mineral Resources, Bulletin 84, 211p.

Mixon, R.B., 1985, Stratigraphic and Geomorphic Framework of Uppermost Cenozoic Deposits in the Southern Delmarva Prninsula, Virginia and Maryland: USGS Professional Paper 1607-G, 53 p.

Murray, K., and Wade, P., 1996, Checking anion-cation charge balance of water quality analyses: Limitations of the traditional method for non-potable waters. Water SA, vol. 22(1), pp 27-32.

Nelms, D.L., and Moberg, R.M., 2010, Hydrogeology and Groundwater Availability in Clarke County, Virginia: United States Geological Survey Scientific Investigations Report 2010-5112, 119 p.

Oertel, G.F., and Foyle, A.M., 1995, Drainage displacement by sea-level fluctuation at the outer margin of the Chesapeake seaway: Jounal of Coastal Research, 11(3): 583-604.

Puckett, L.J., Tesoriero, A., and Dubrovsky, N.M., 2011, Nitrogen Contamination of Surficial Aquifers - A Growing Legacy: Environmental Science and Technology, v. 45, p. 839-844.

Reese, S., and Lee, J.J., 1999, Trend Analysis of Regional Groundwater Data, Southeastern Pennsylvania: Pennsylvania Department of Environmental Protection Bureau of Water Supply Management, 11p.

Sanford, W.E., Pope, J.P., and Nelms, D.L., 2009, Simulation of groundwater-level and salinity changes in the Eastern Shore, Virginia: U.S. Geological Survey Scientific Investigations Report 2009-5066, 125 p.

Southworth, S., Bailey, C.M., Eaton, L.S., Hancock, G., Lamoreaux, M.H., Litwin, R.J., Burton, W.C., and Whitten, J., 2009, Geology of the Shenandoah National Park Region; Virginia Geology Field Conference Guidebook: Harrisonburg, Va., James Madison University, 40 p.

Steeves, P., and Nebert, D., 1994, 1:250,000-scale Hydrologic Units of the United States: U.S. Geological Survey Open File Report 94-0236, scale 1:250,000.

U.S. Environmental Protection Agency, 2009, Statistical Analysis of Groundwater Monitoring Data at RCRA Facilities: EPA 530/R-09-007, 888 p

U.S. Geological Survey, 2006, Collection of water samples (ver 2.0): U.S. Geological Survey Techniques of Water-Resources Investigations, Book 9, chap A4.

U.S. Geological Survey, variously dated, National field manual for the collction of water-quality data: U.S. Geological Survey Techniques of Water-Resources Investigations, book 9, chaps. A1-A9, available online at http://pubs.water.usgs.gov/twri9A.

Virginia Department of Environmental Quality, 2009, Standard Operating Procedures Manual for the Department of Environmental Quality - Water Quality Monitoring and Assessment Program, WQM SOP, 169p.

Virginia Department of Health, 2005, Plan of Action for Arsenic in Drinking Water: Virginia Department of Health Office of Drinking Water, 19 p.

Virginia Division of Mineral Resources, 1993, Geologic Map of Virginia: Virginia Division of Mineral Resources, scale 1:500,000.

Water Systems Council, 2012, Well Care - Virginia Fact Sheet: Water Systems Council Fact Sheet, 2 p.

White, B.A., 2012, Groundwater Resources of the Blue Ridge Geologic Province, Virginia: Virginia DEQ Technical Bulletin 12-01, 209 p.

White, B.A., Maynard, J.P., Beach, T.A., and Bruce, T.S., 2013, Groundwater Geochemical Database of Virginia. Virginia Department of Environmental Quality: Richmond, Virginia Department of Environmental Quality.

Williams, L.J., Kath, R.L., Crawford, T.J., and Chapman, M.J., 2005, Influence of Geologic Setting on Ground Water Availability in the Lawrenceville Area, Gwinnett County, Georgia: U.S. Geological Survey Scientific Investigations Report 2005-5136, 43 p.

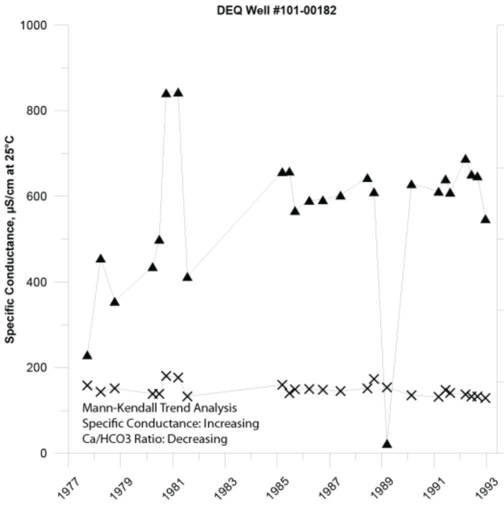
Wright, W.G., 1990, Ground-Water Hydrology and Quality in the Valley and Ridge and Blue Ridge Physiographic Provinces of Clarke County, Virginia: USGS Water-Resources Investigations Report 90-4134, 67 p.

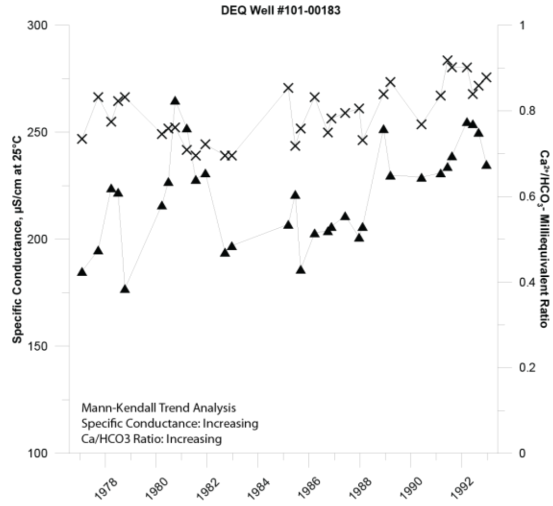
APPENDIX A

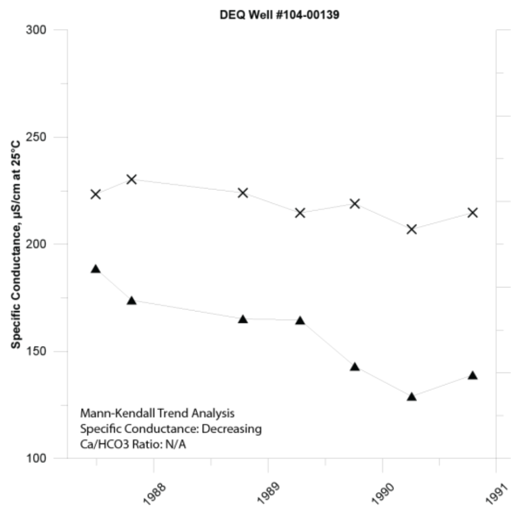
Water Quality Summary Plots for

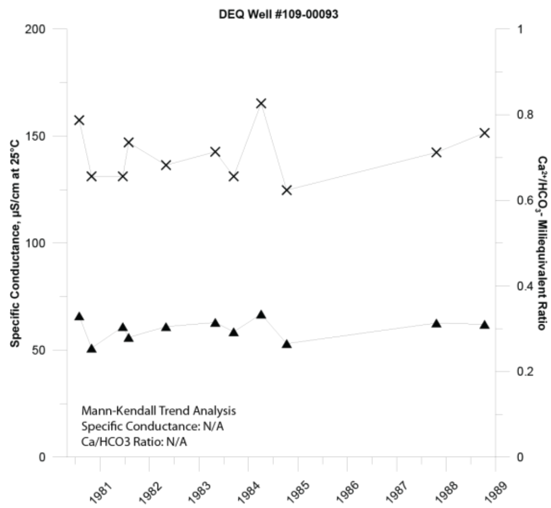
Wells Used in Trend Analysis

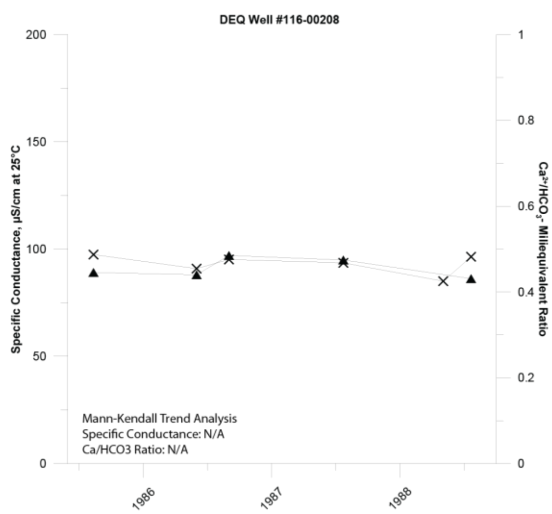
Undifferentiated Crystalline Rock

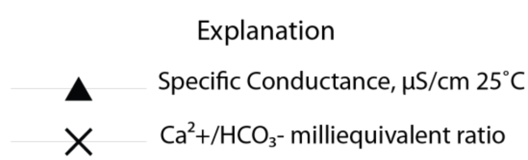




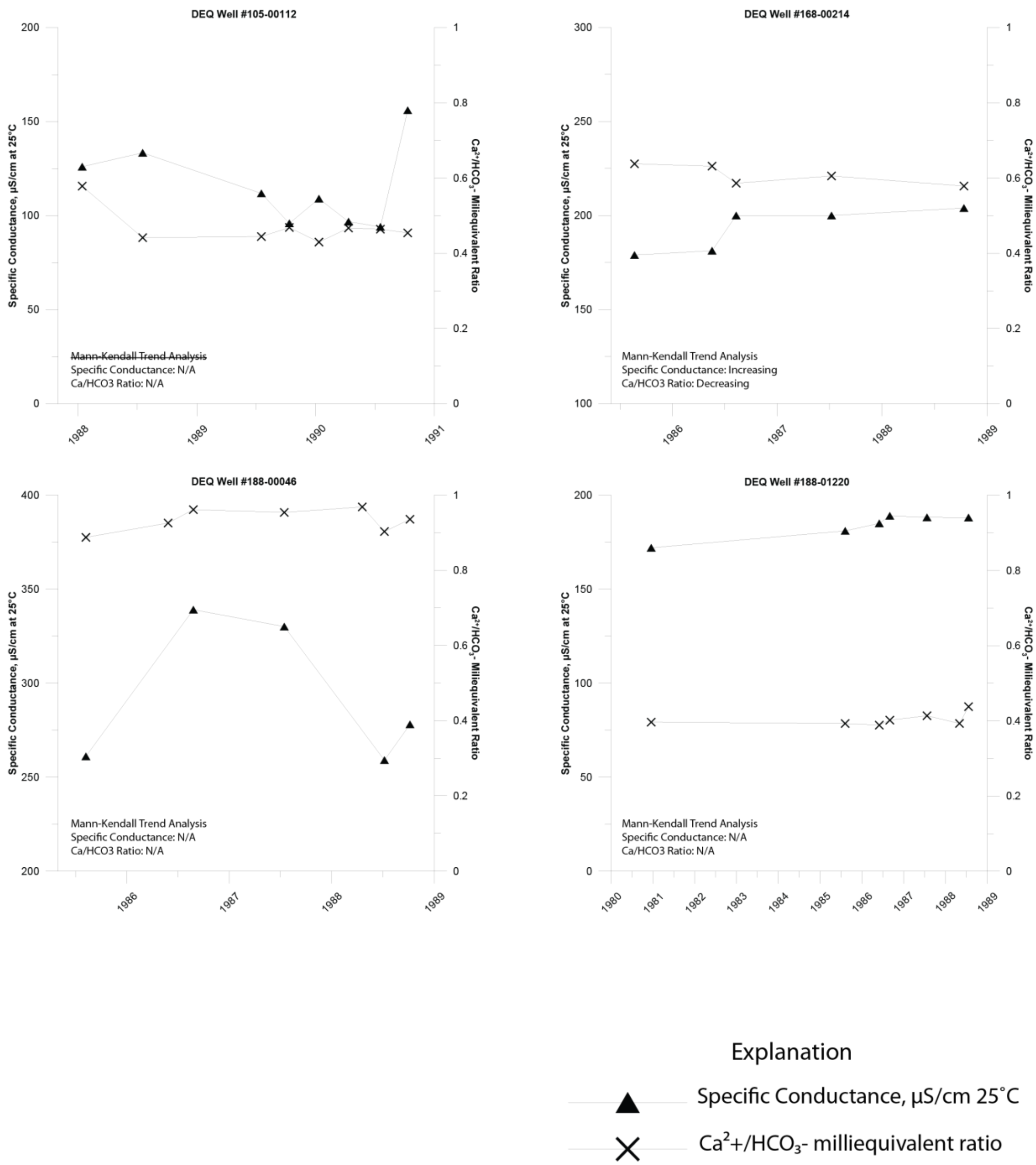




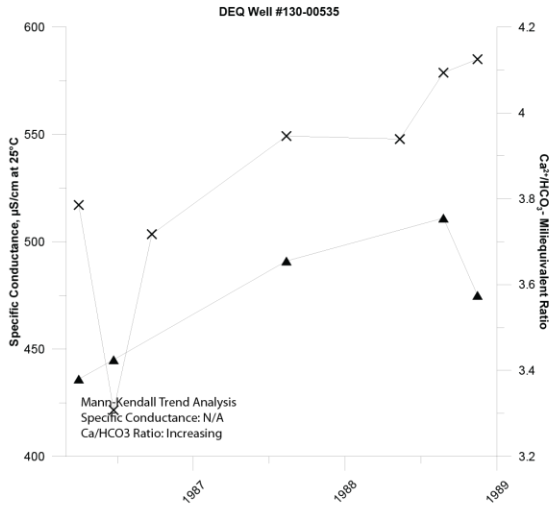


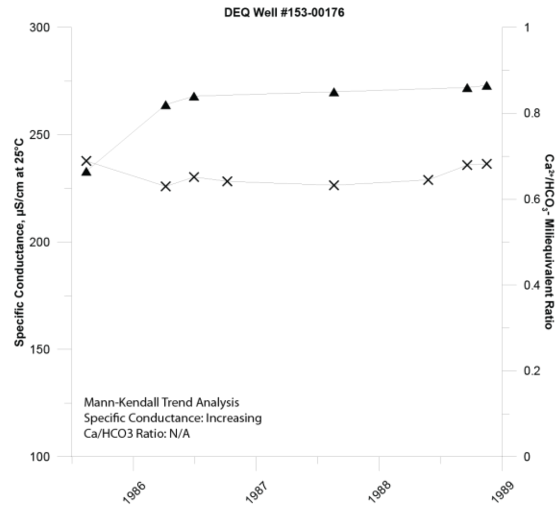


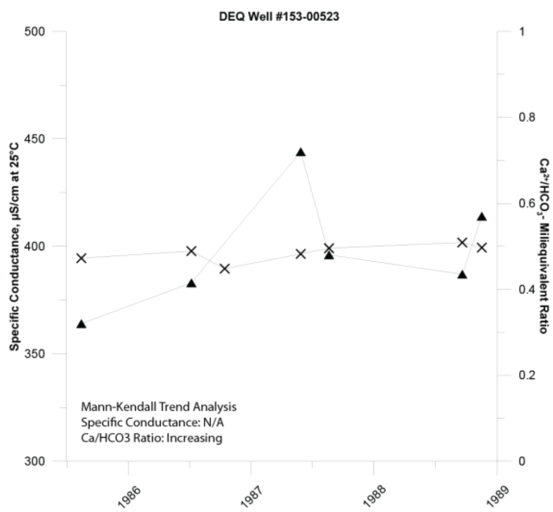
Chopawamsic Volcanic Rocks

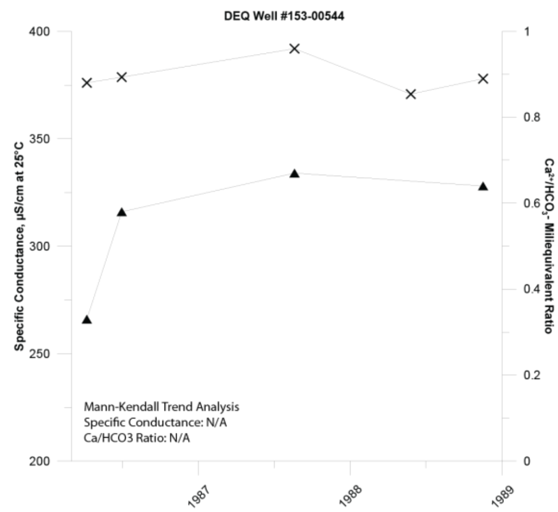


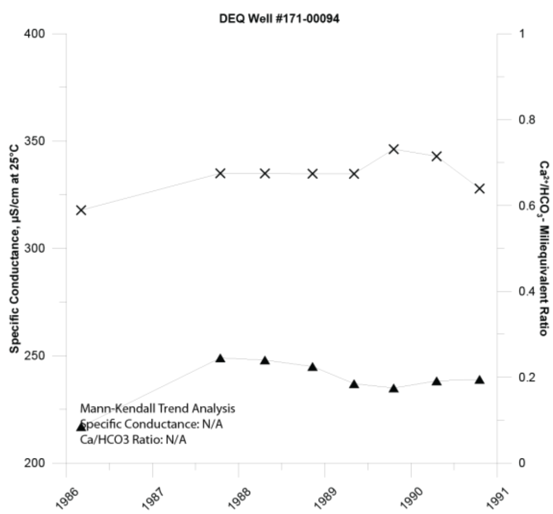
Mesozoic Basins

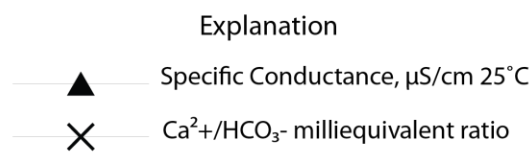




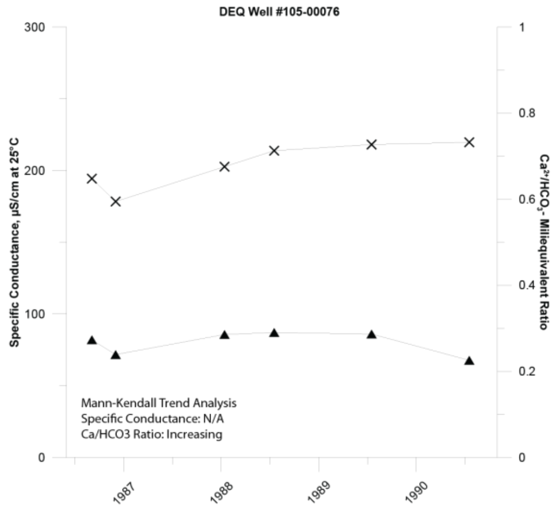


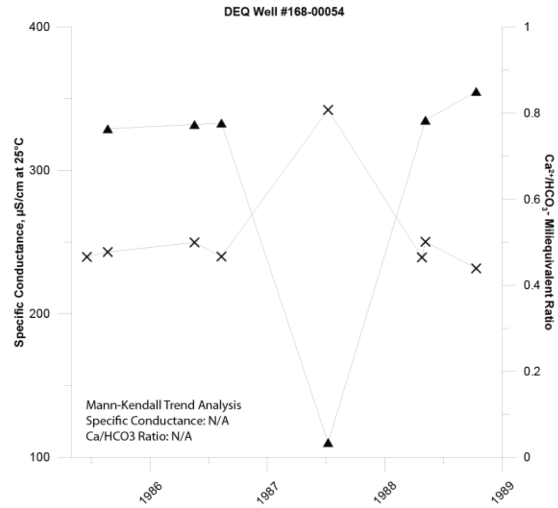


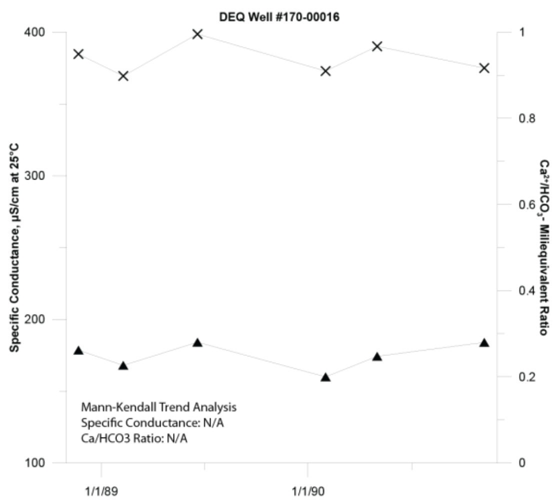


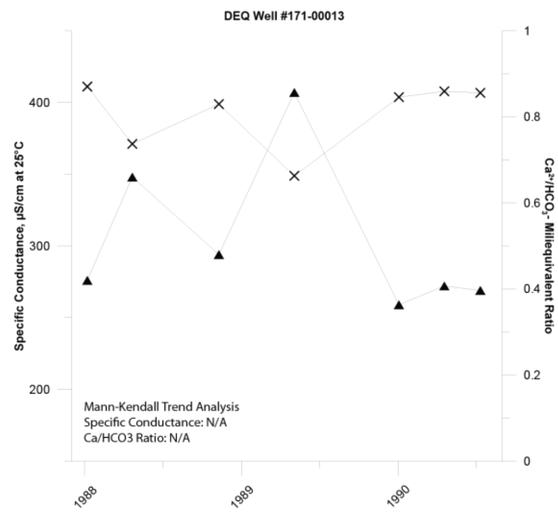


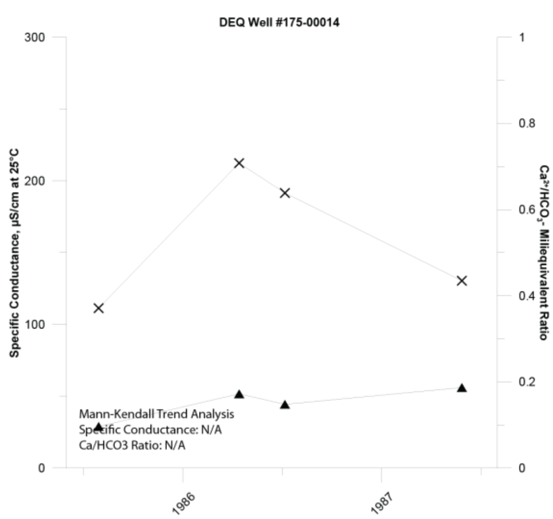
Western Piedmont









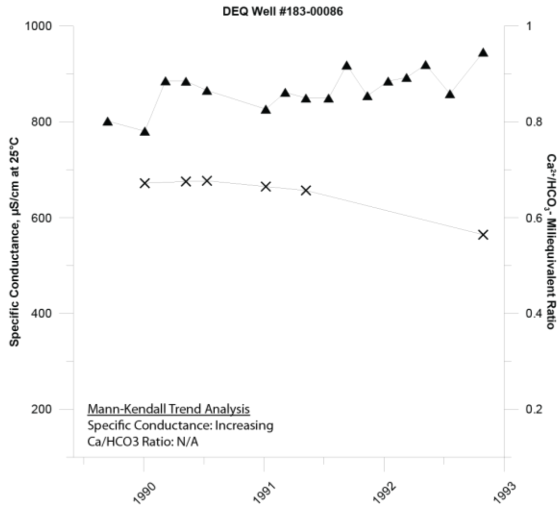


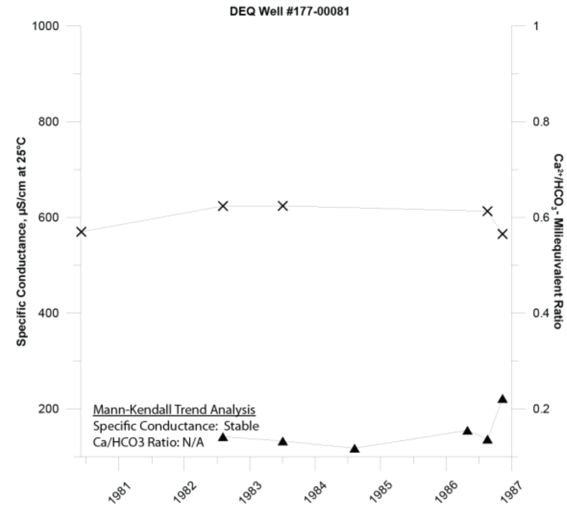
Explanation

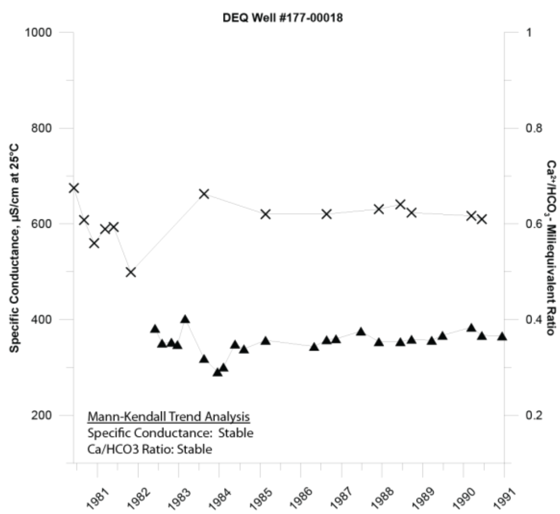
▲ Specific Conductance, µS/cm 25°C

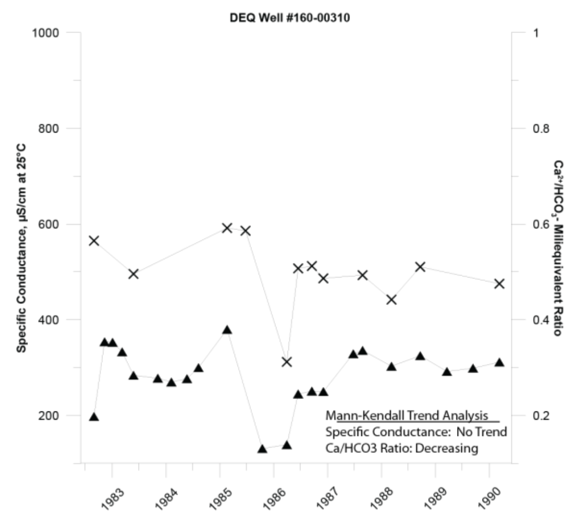
× Ca^2+/HCO_3- milliequivalent ratio

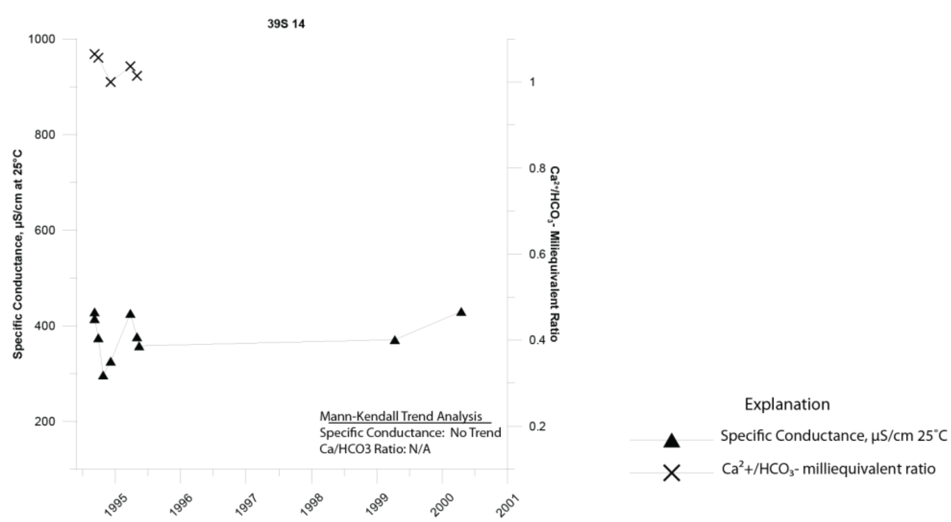
Cambrian Siliciclastics

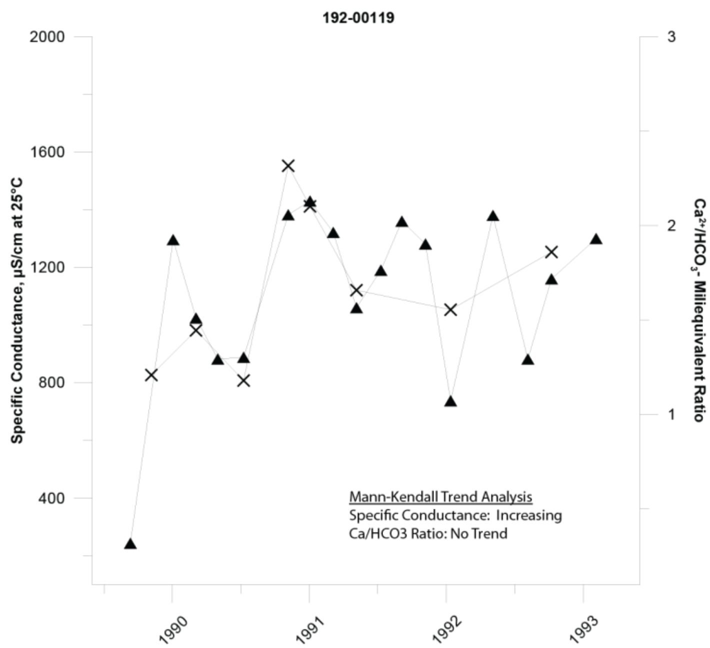


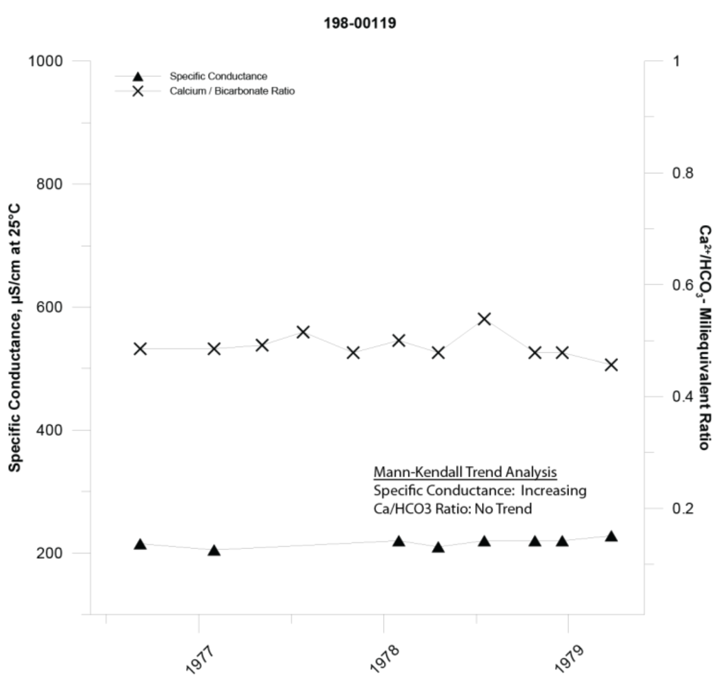




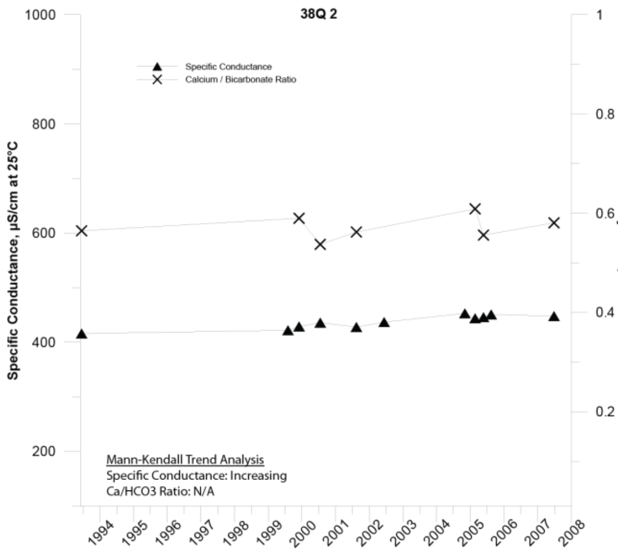


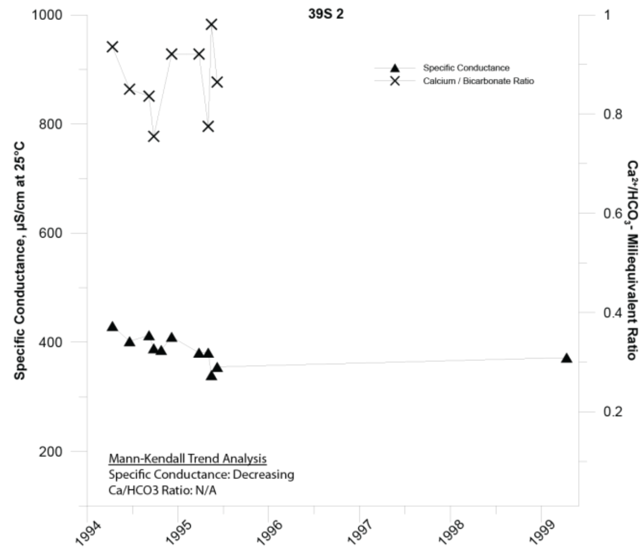


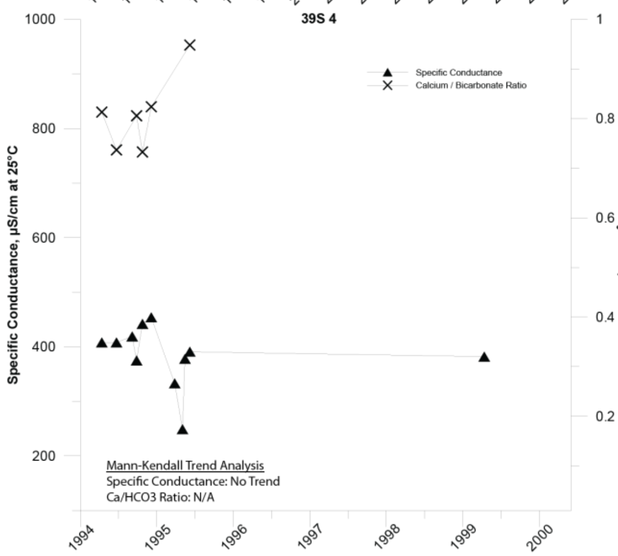

192-00119
Specific Conductance, µS/cm at 25°C
Ca2+/HCO3- Milliequivalent Ratio
2000
1600
1200
800
400
3
2
1
1990
1991
1992
1993
Mann-Kendall Trend Analysis
Specific Conductance: Increasing
Ca/HCO3 Ratio: No Trend

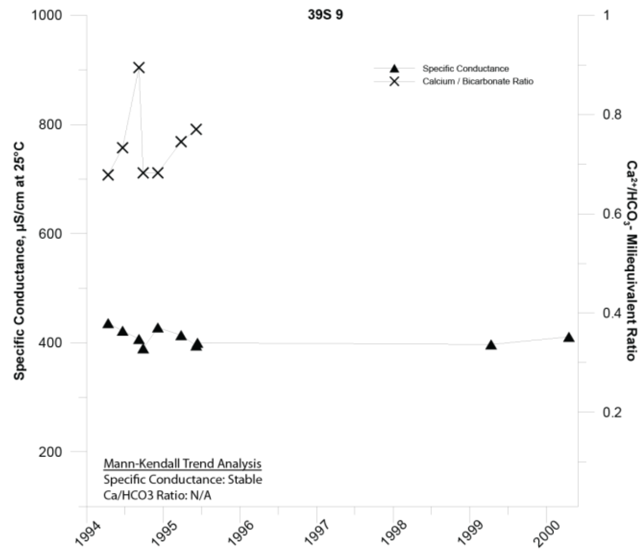

198-00119
Specific Conductance
Calcium / Bicarbonate Ratio
Specific Conductance, µS/cm at 25°C
Ca2+/HCO3- Milliequivalent Ratio
1000
800
600
400
200
1
0.8
0.6
0.4
0.2
1977
1978
1979
Mann-Kendall Trend Analysis
Specific Conductance: Increasing
Ca/HCO3 Ratio: No Trend

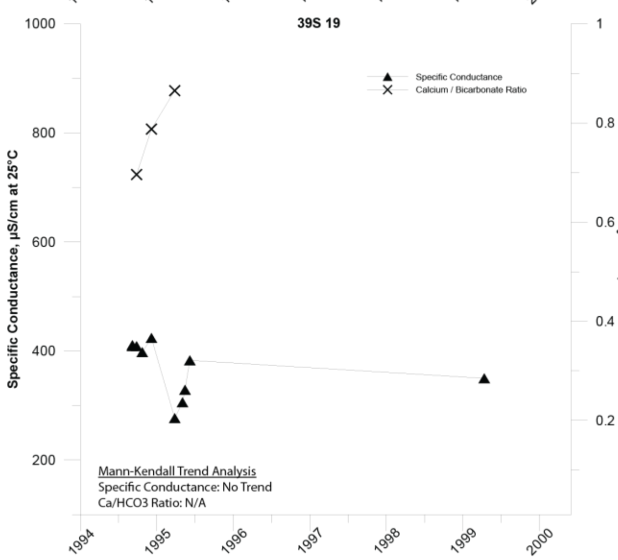
Cambrian - Ordovician Carbonates

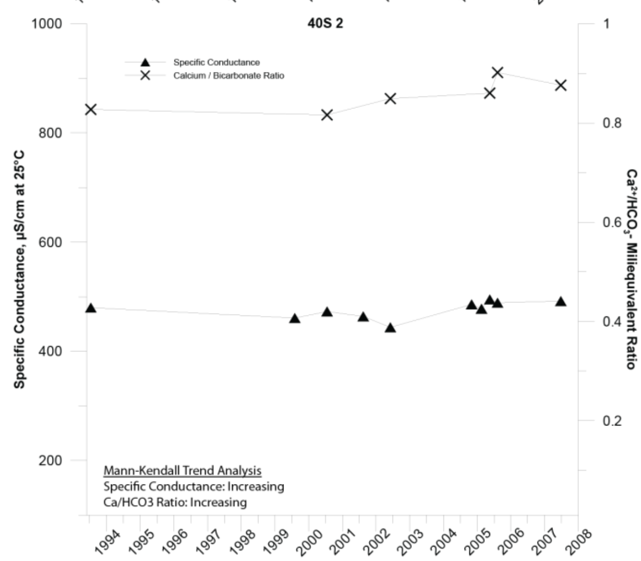




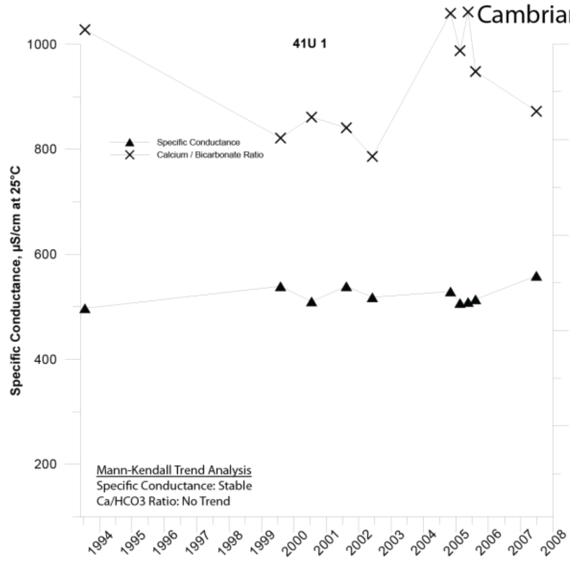


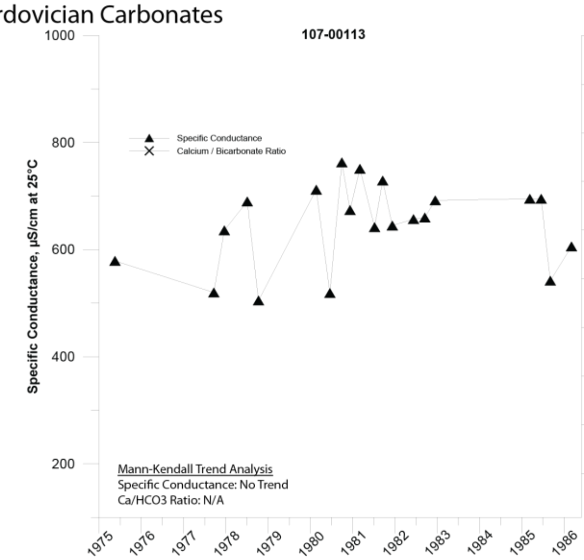


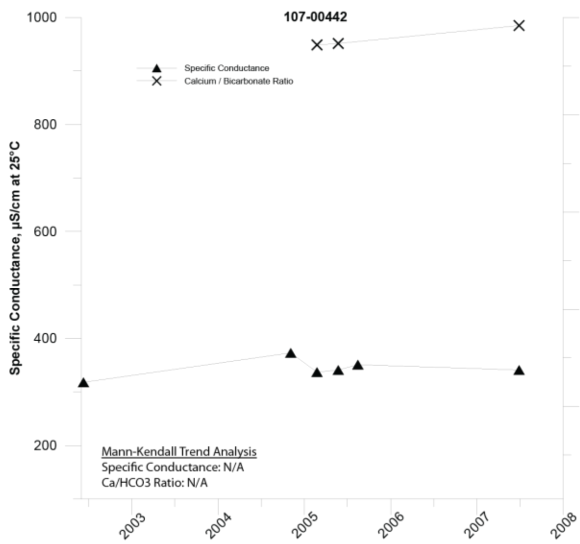


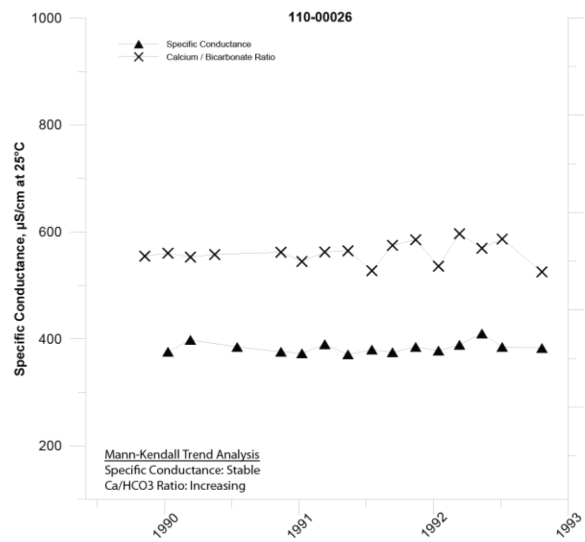


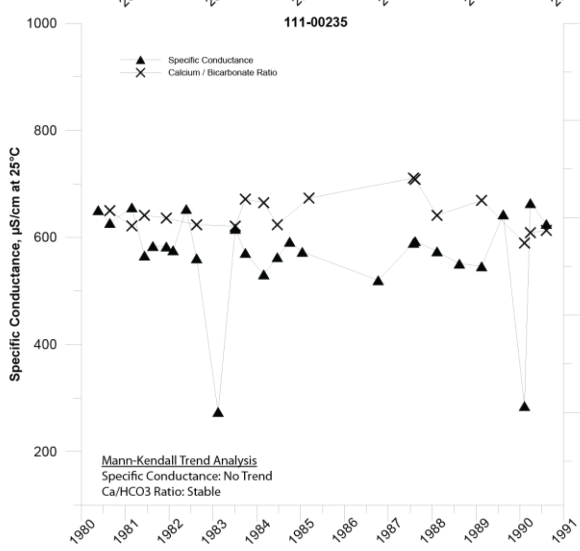
Cambrian - Ordovician Carbonates

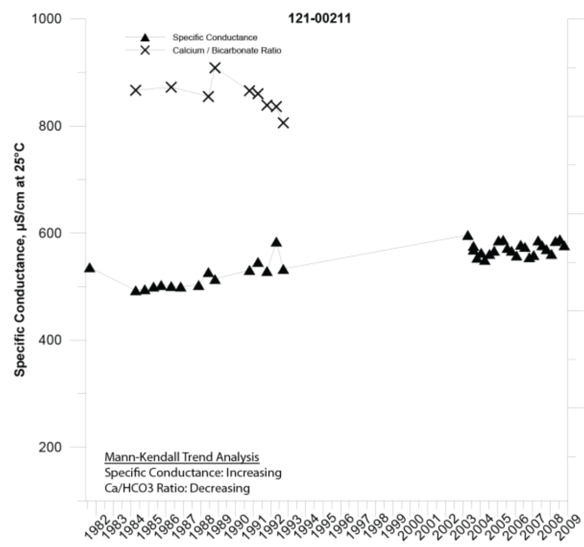




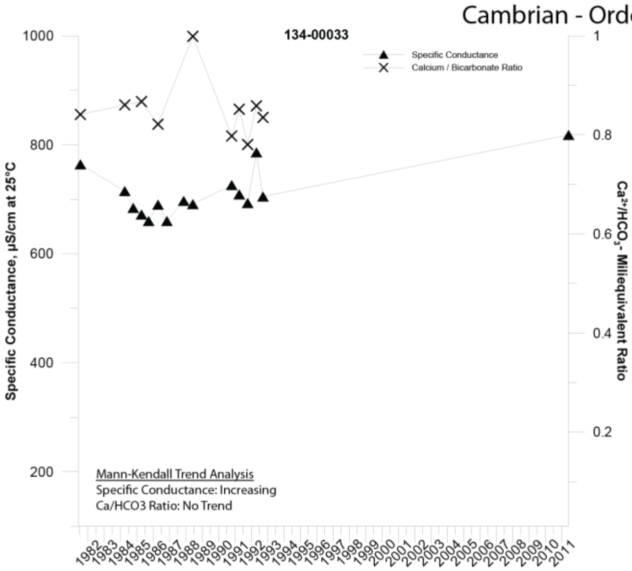


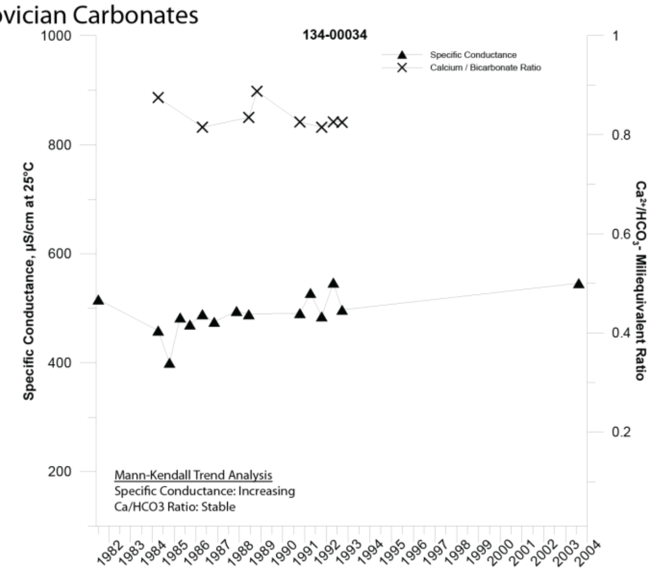


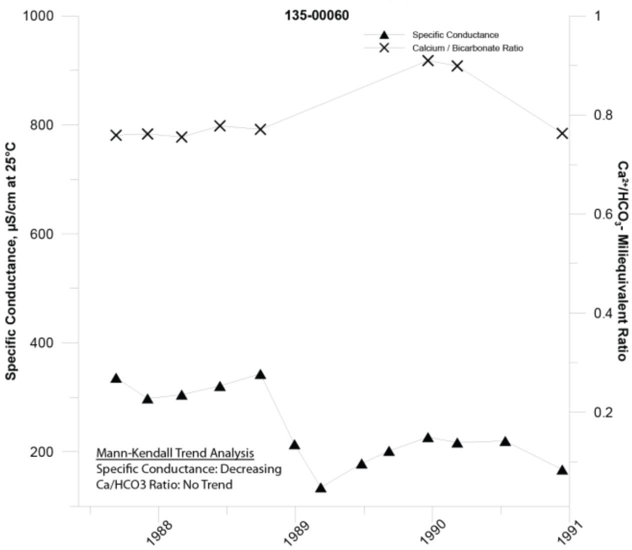


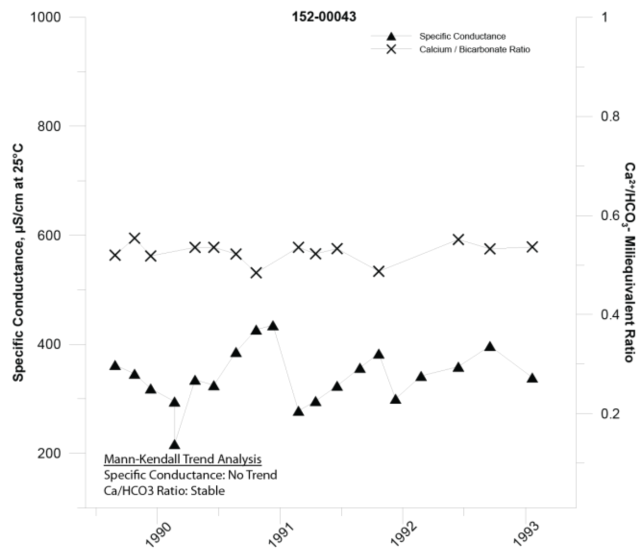


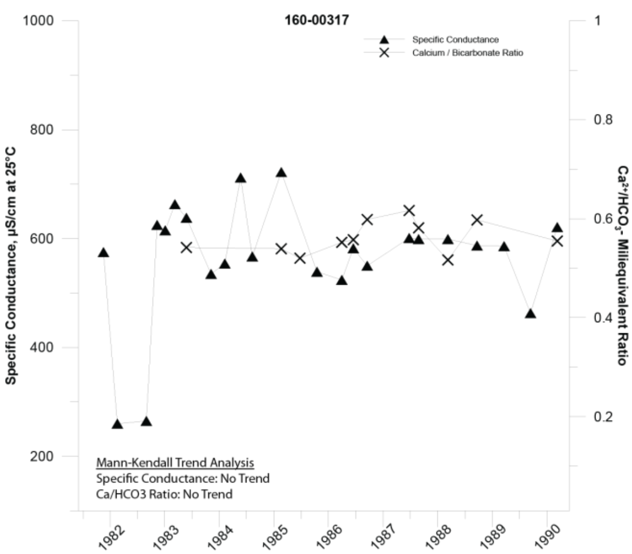
Cambrian - Ordovician Carbonates

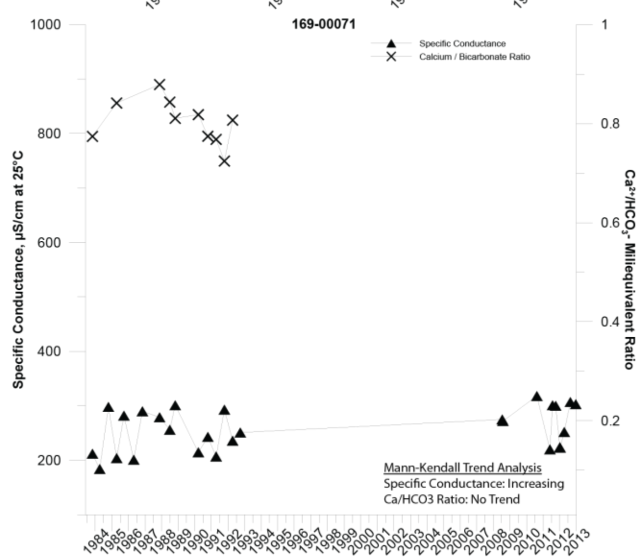




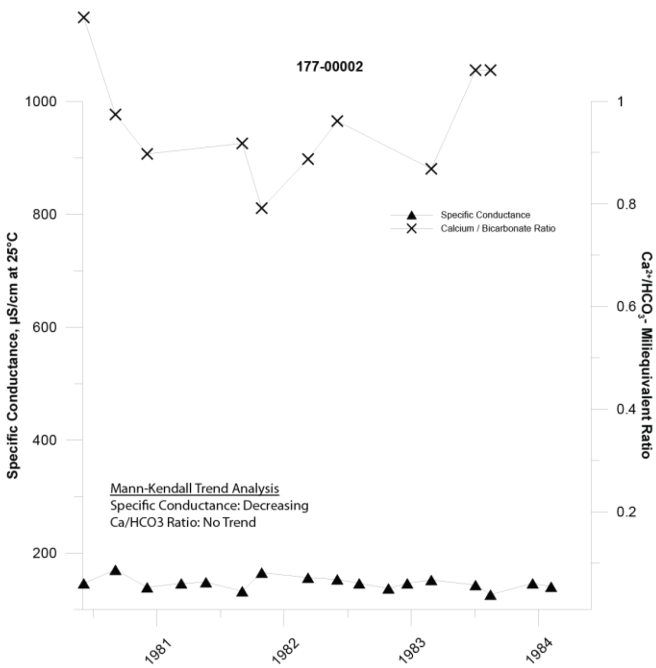


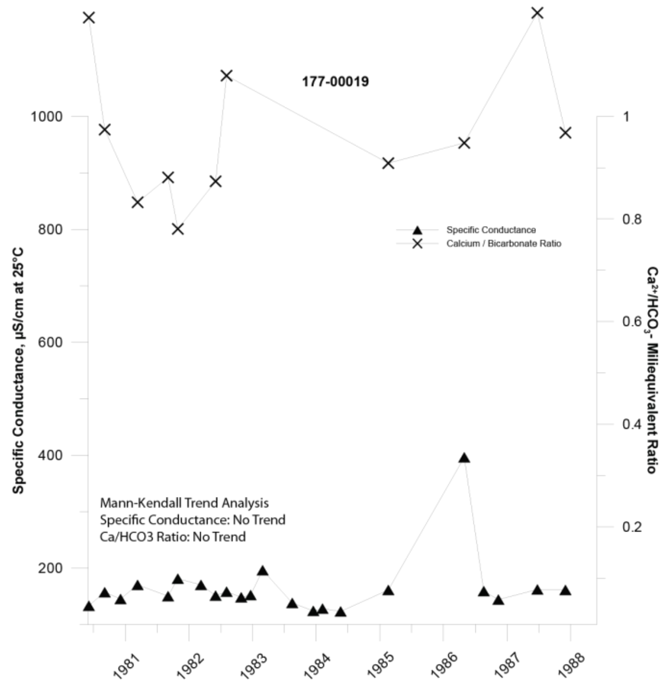


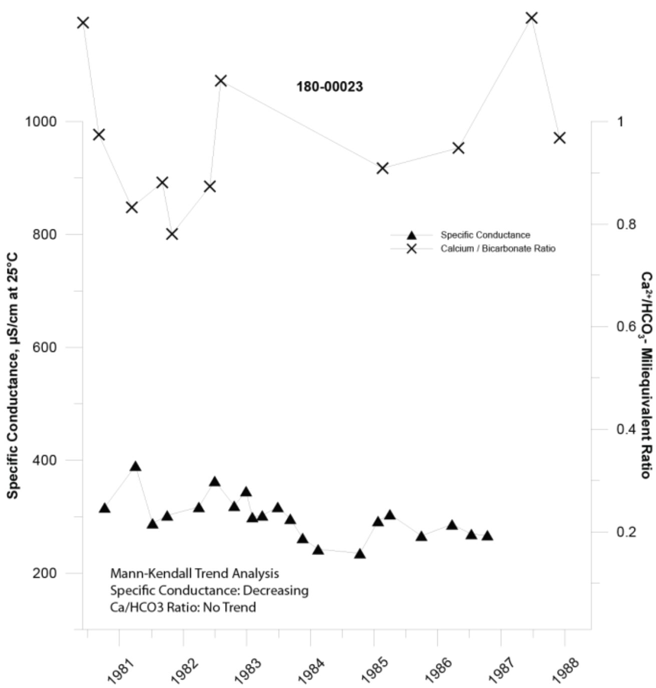


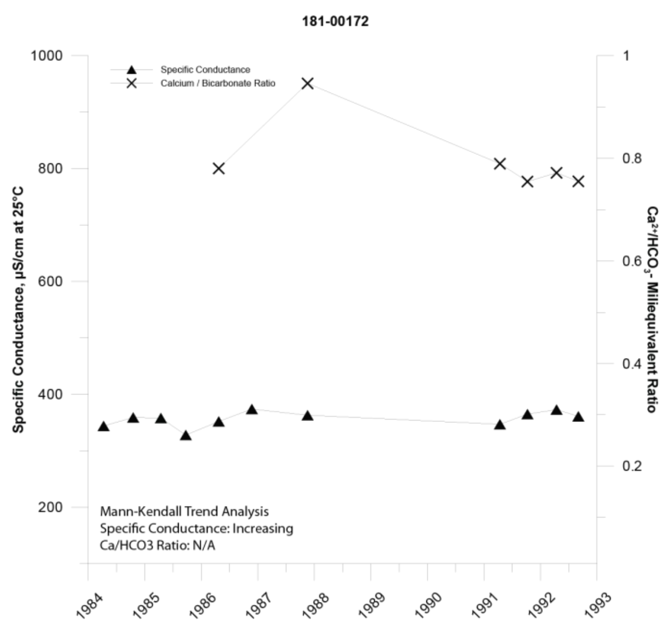


Cambrian - Ordovician Carbonates

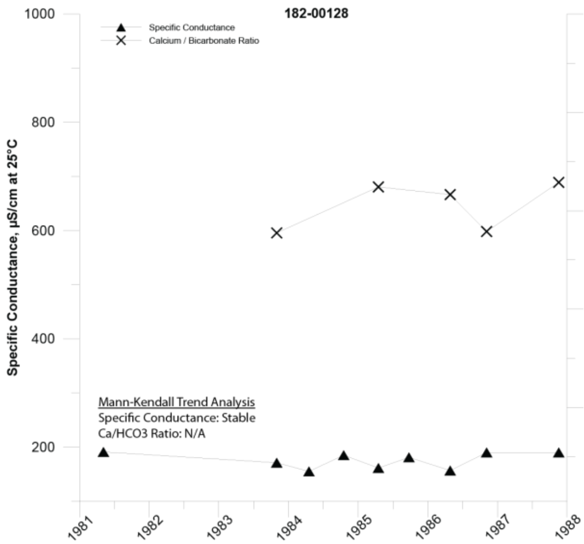


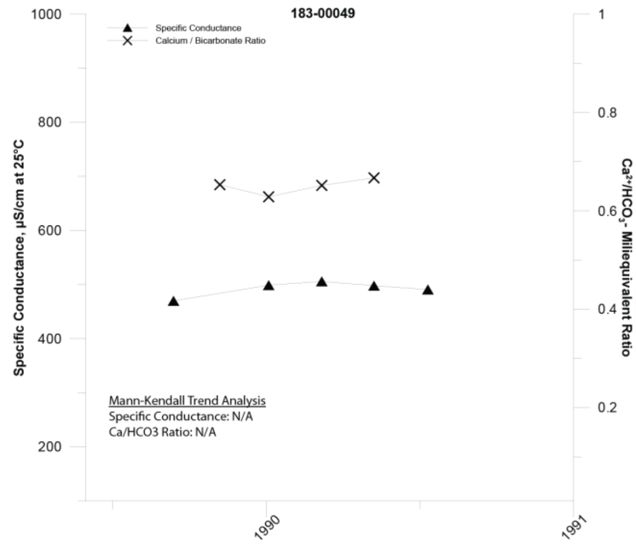


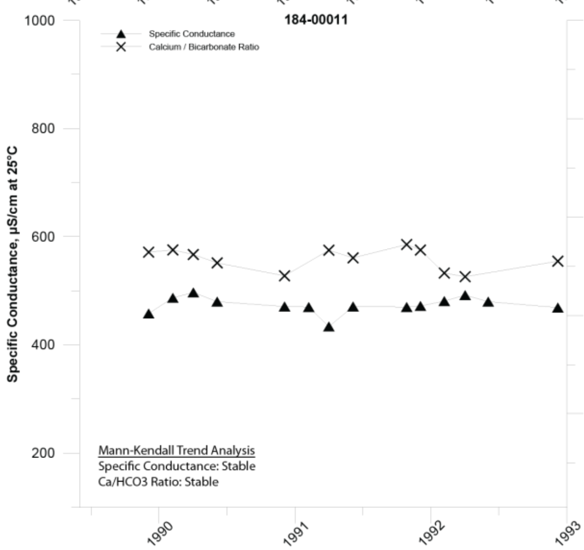


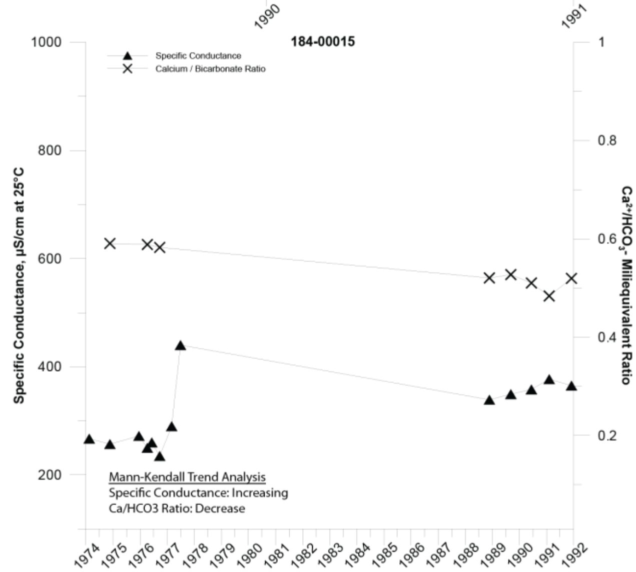


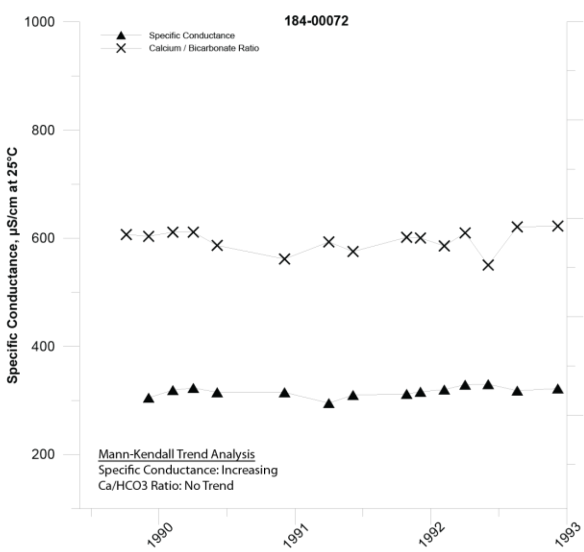
Cambrian - Ordovician Carbonates

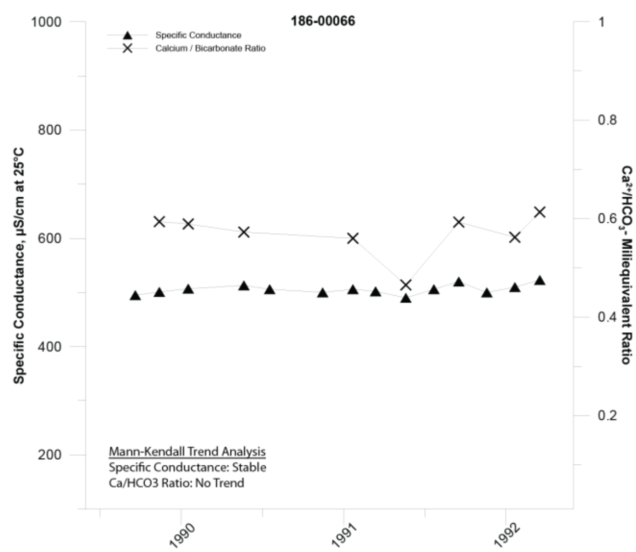




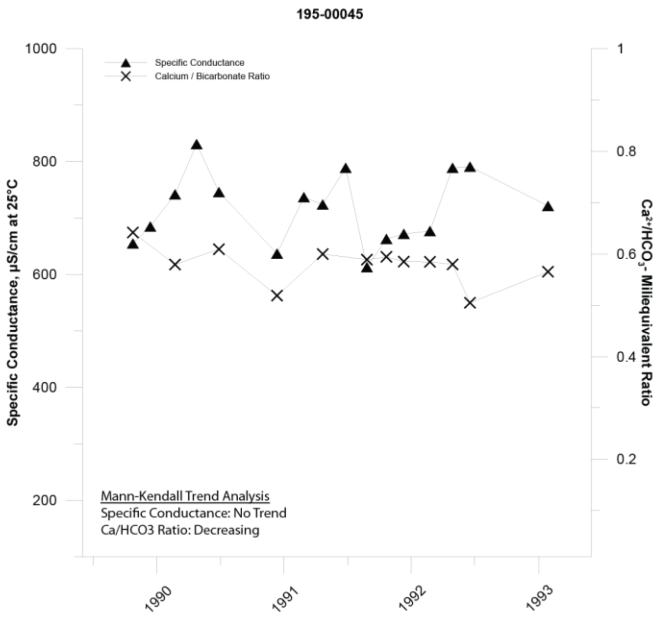


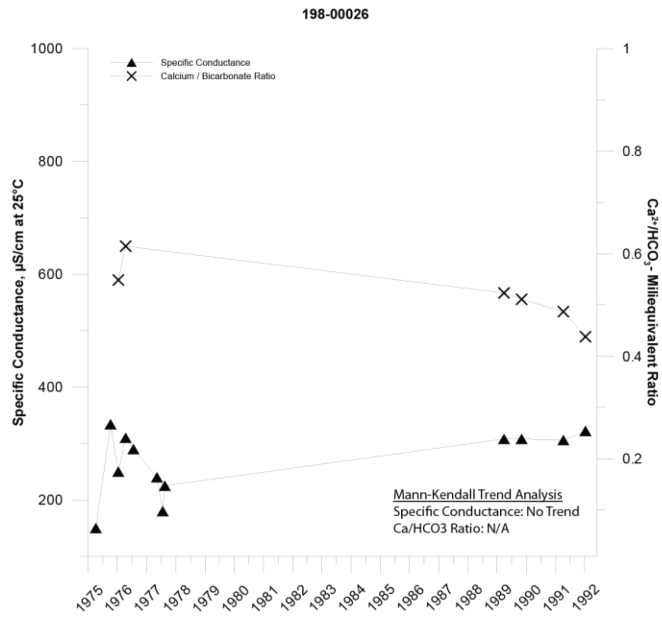


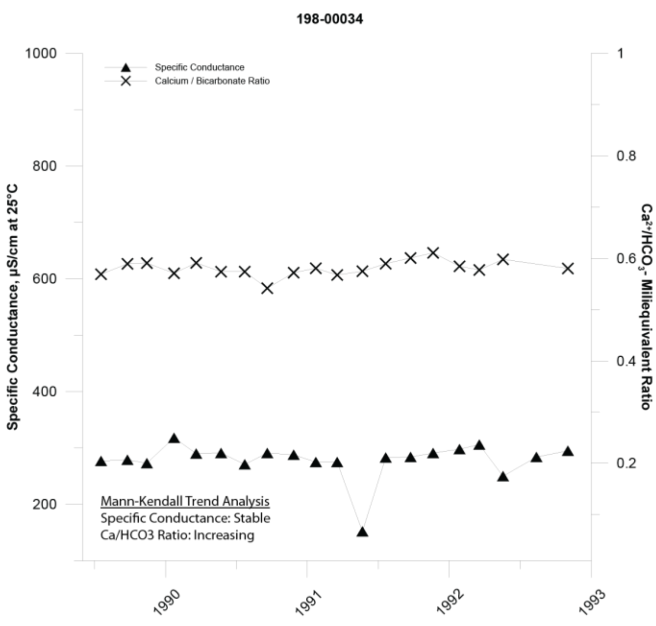


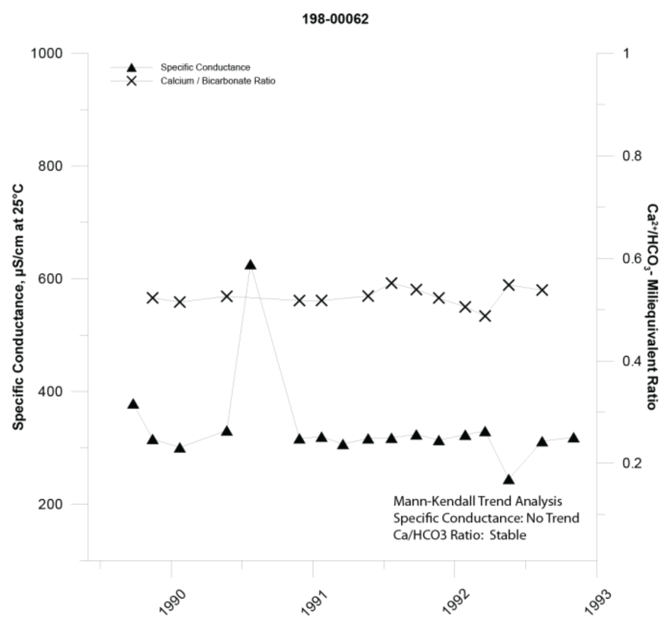


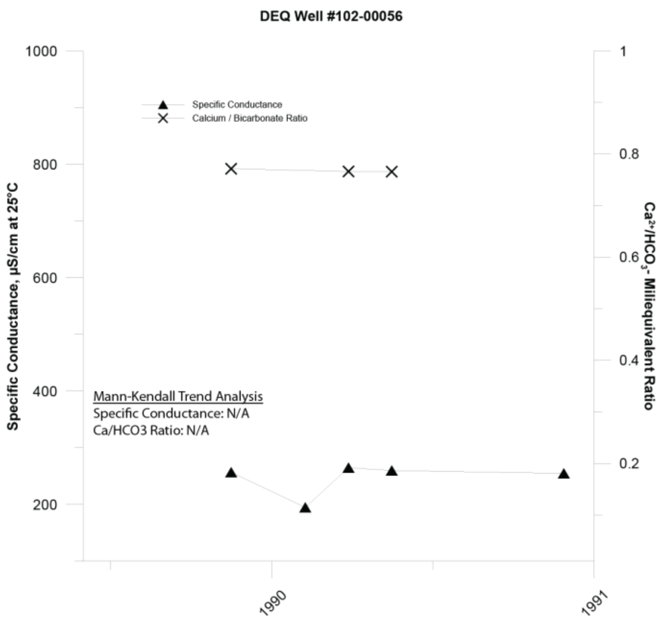
Cambrian - Ordovician Carbonates

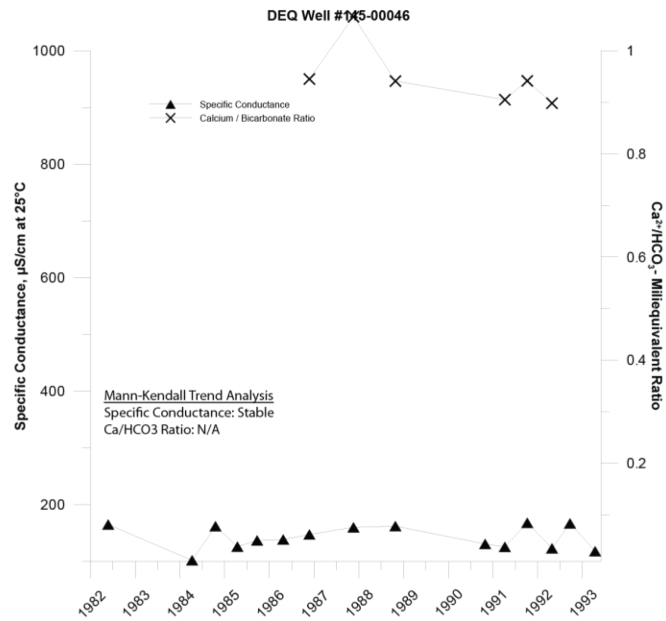


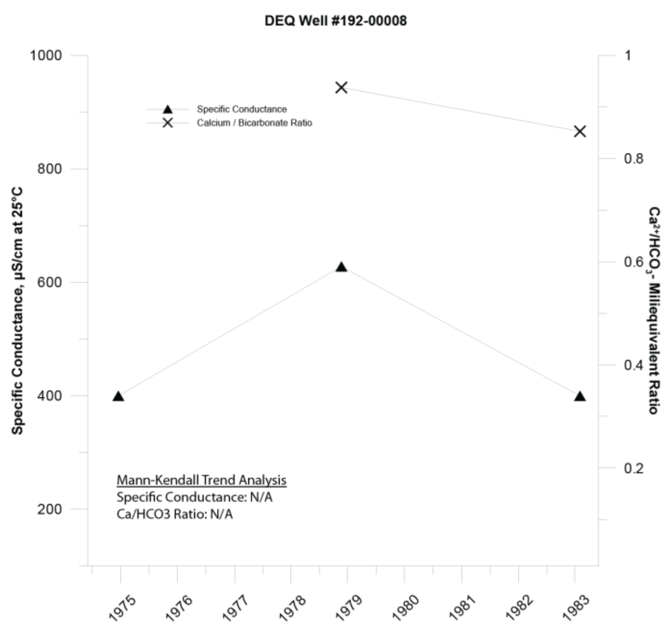




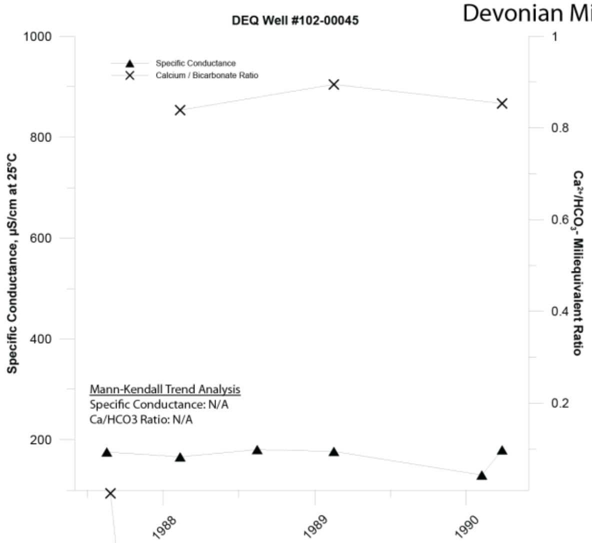


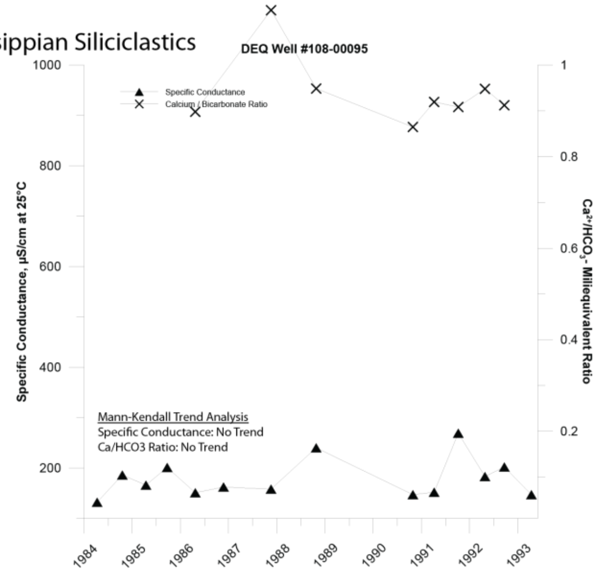

DEQ Well #102-00056
Specific Conductance
Calcium / Bicarbonate Ratio
Specific Conductance, µS/cm at 25°C
Ca²⁺/HCO₃⁻ Milliequivalent Ratio
Mann-Kendall Trend Analysis
Specific Conductance: N/A
Ca/HCO3 Ratio: N/A
1000
800
600
400
200
1
0.8
0.6
0.4
0.2
1990
1991

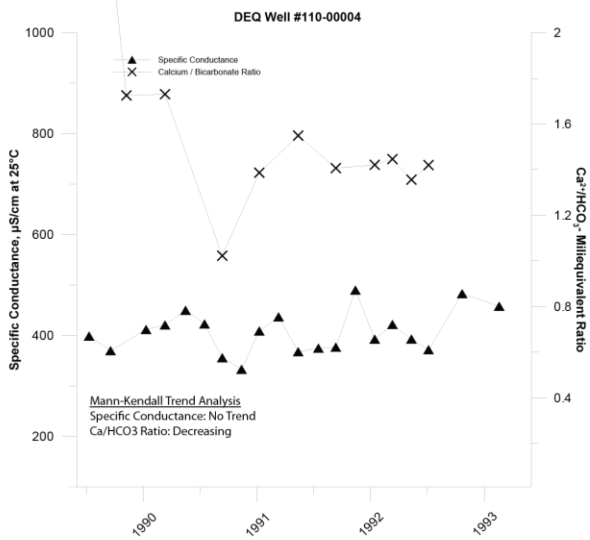

DEQ Well #145-00046
Specific Conductance
Calcium / Bicarbonate Ratio
Specific Conductance, µS/cm at 25°C
Ca²⁺/HCO₃⁻ Milliequivalent Ratio
Mann-Kendall Trend Analysis
Specific Conductance: Stable
Ca/HCO3 Ratio: N/A
1000
800
600
400
200
1
0.8
0.6
0.4
0.2
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993

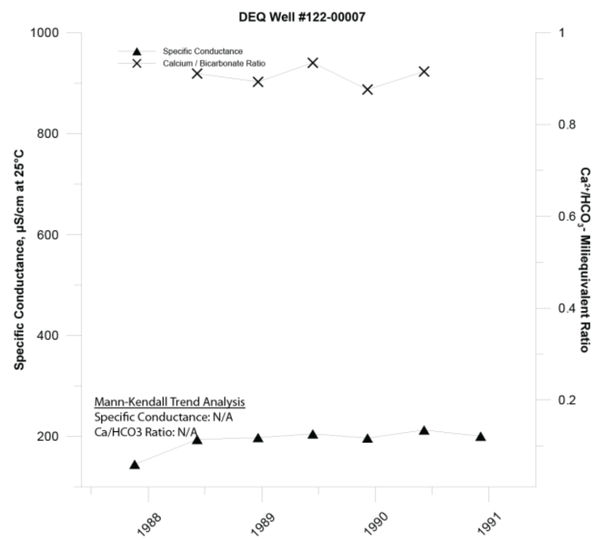

DEQ Well #192-00008
Specific Conductance
Calcium / Bicarbonate Ratio
Specific Conductance, µS/cm at 25°C
Ca²⁺/HCO₃⁻ Milliequivalent Ratio
Mann-Kendall Trend Analysis
Specific Conductance: N/A
Ca/HCO3 Ratio: N/A
1000
800
600
400
200
1
0.8
0.6
0.4
0.2
1975
1976
1977
1978
1979
1980
1981
1982
1983

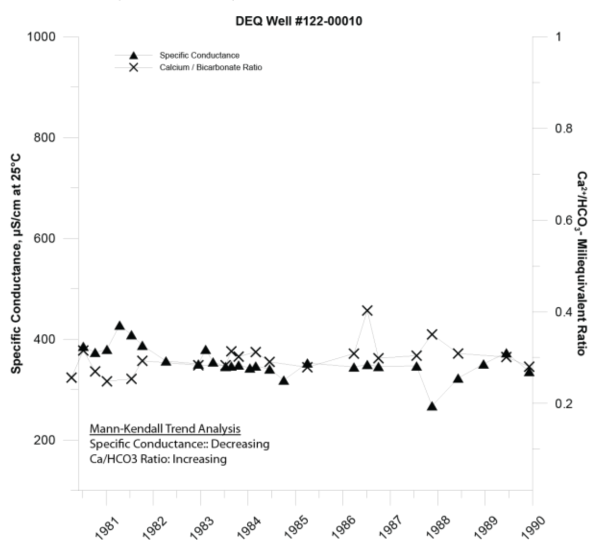
Devonian Mississippian Siliciclastics

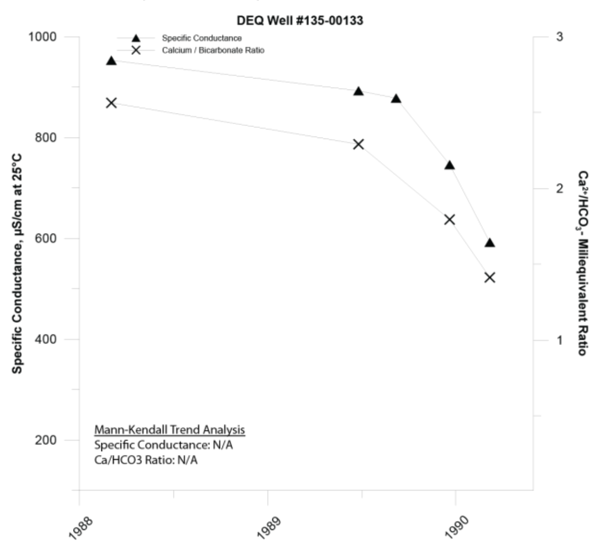




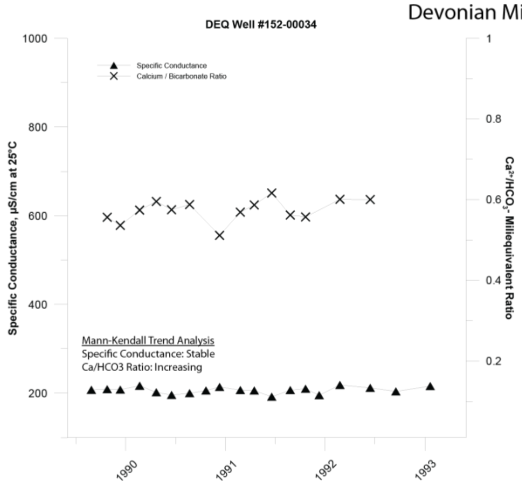


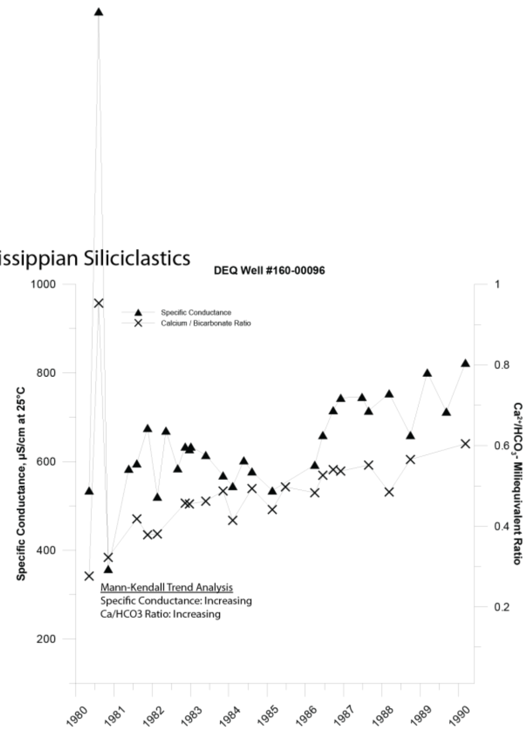


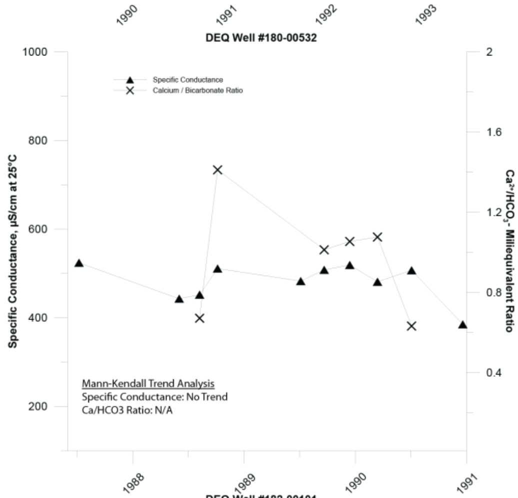


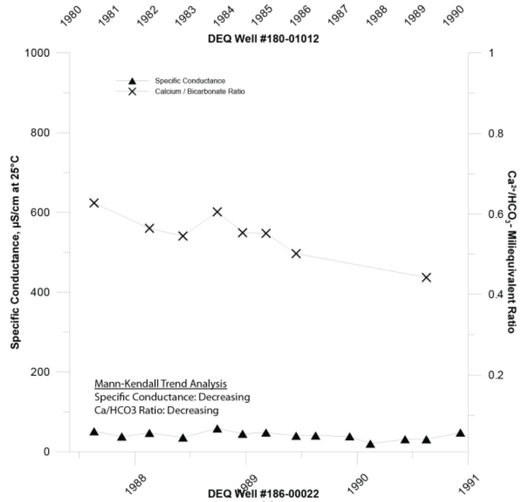


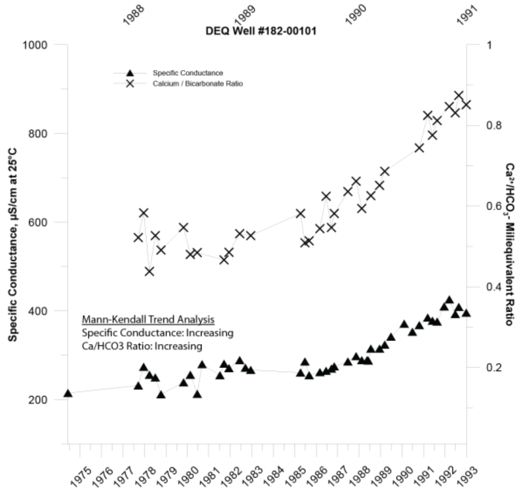
Devonian Mississippian Siliciclastics

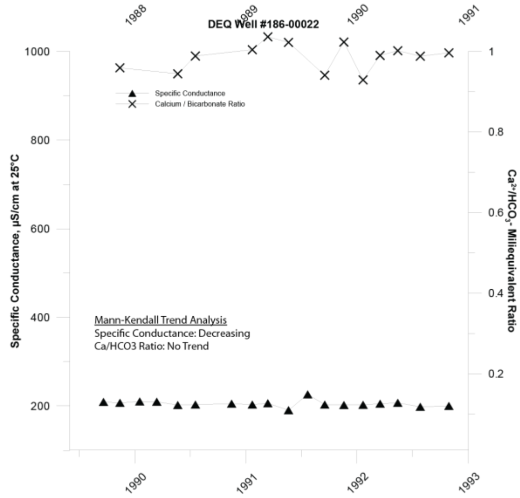




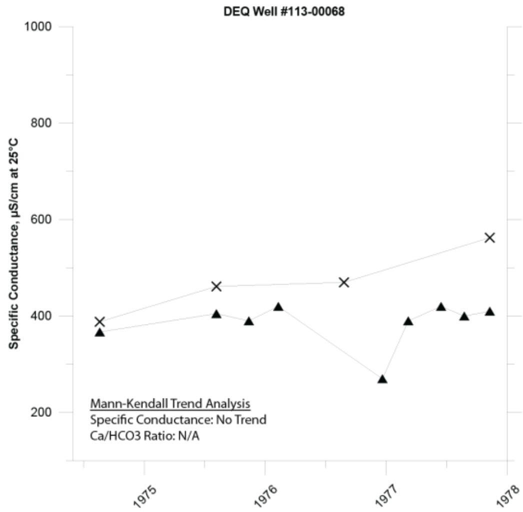


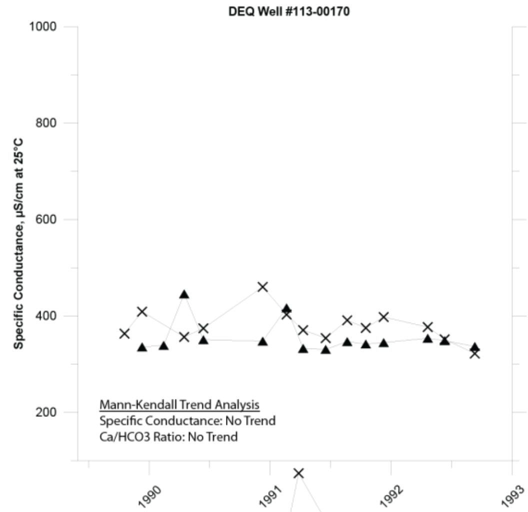


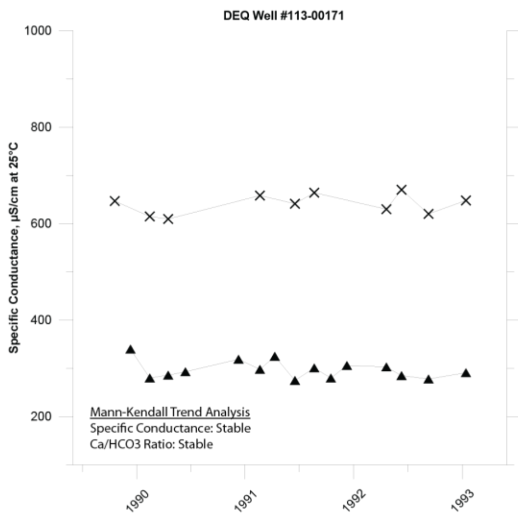


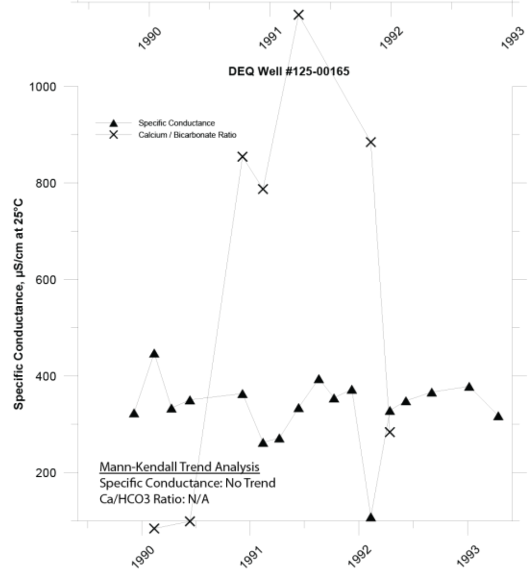


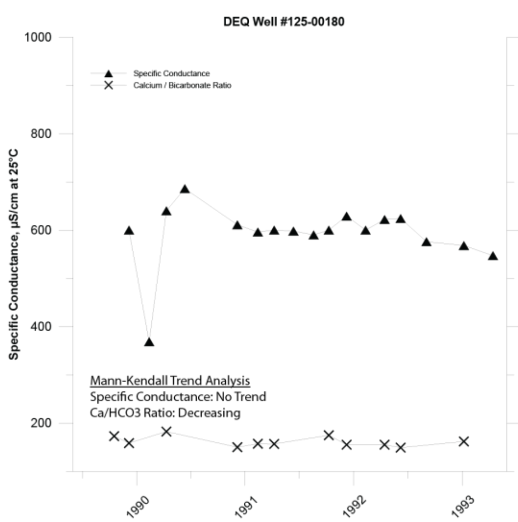
Pennsylvanian Siliciclastics

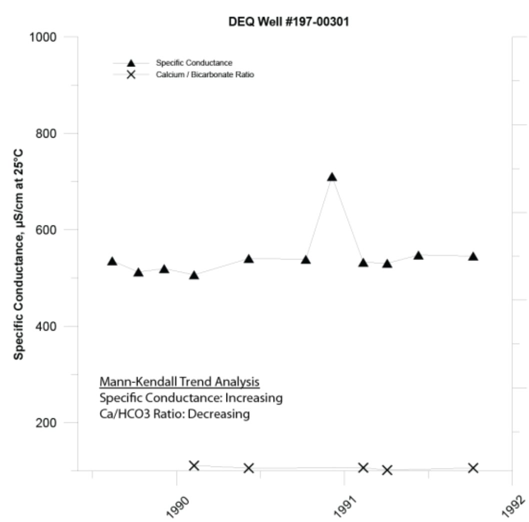




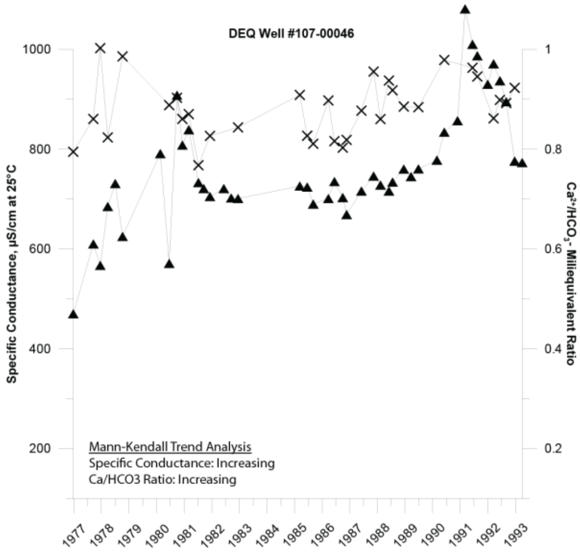


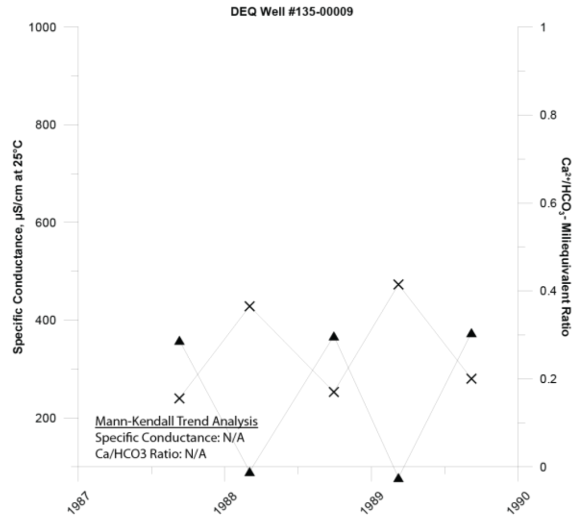


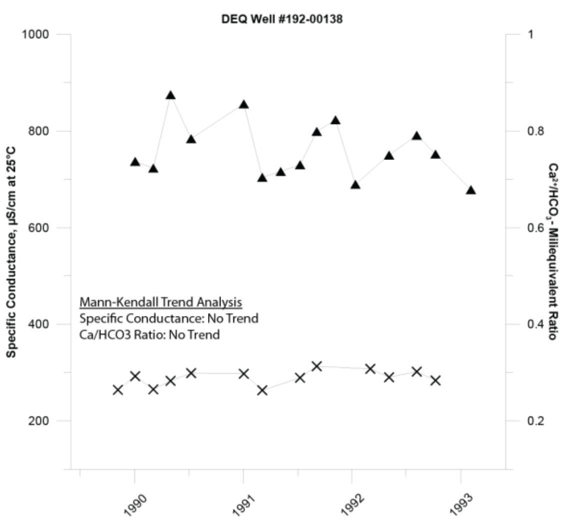


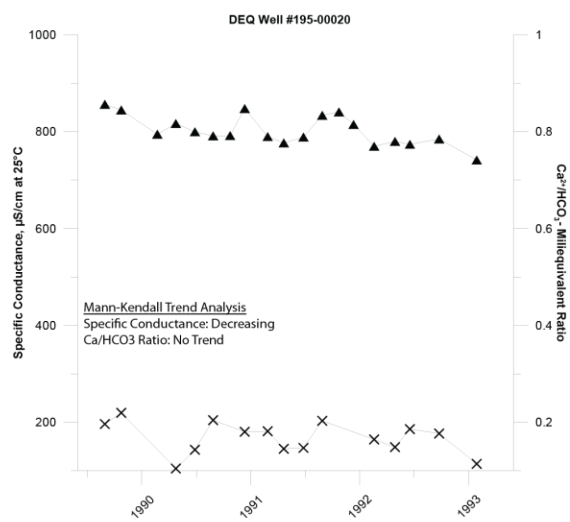


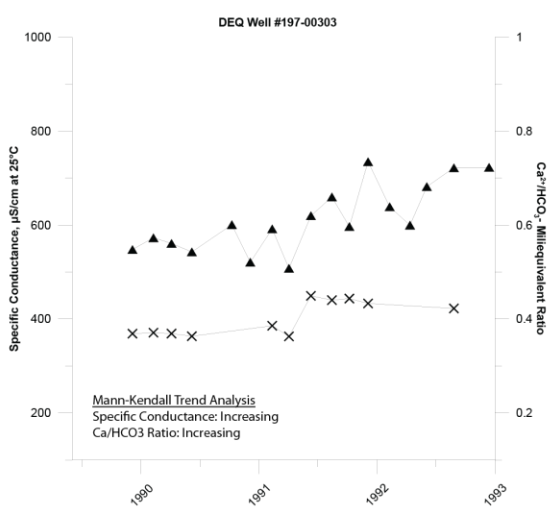
Siluro-Ordovician Siliciclastics











APPENDIX B

Data Used for Evaluation of

Proposed Tier 1 and Tier 2

Chloride Monitoring Wells

Preliminary Tier 1 and Tier 2 Chloride Monitoring sampling locations

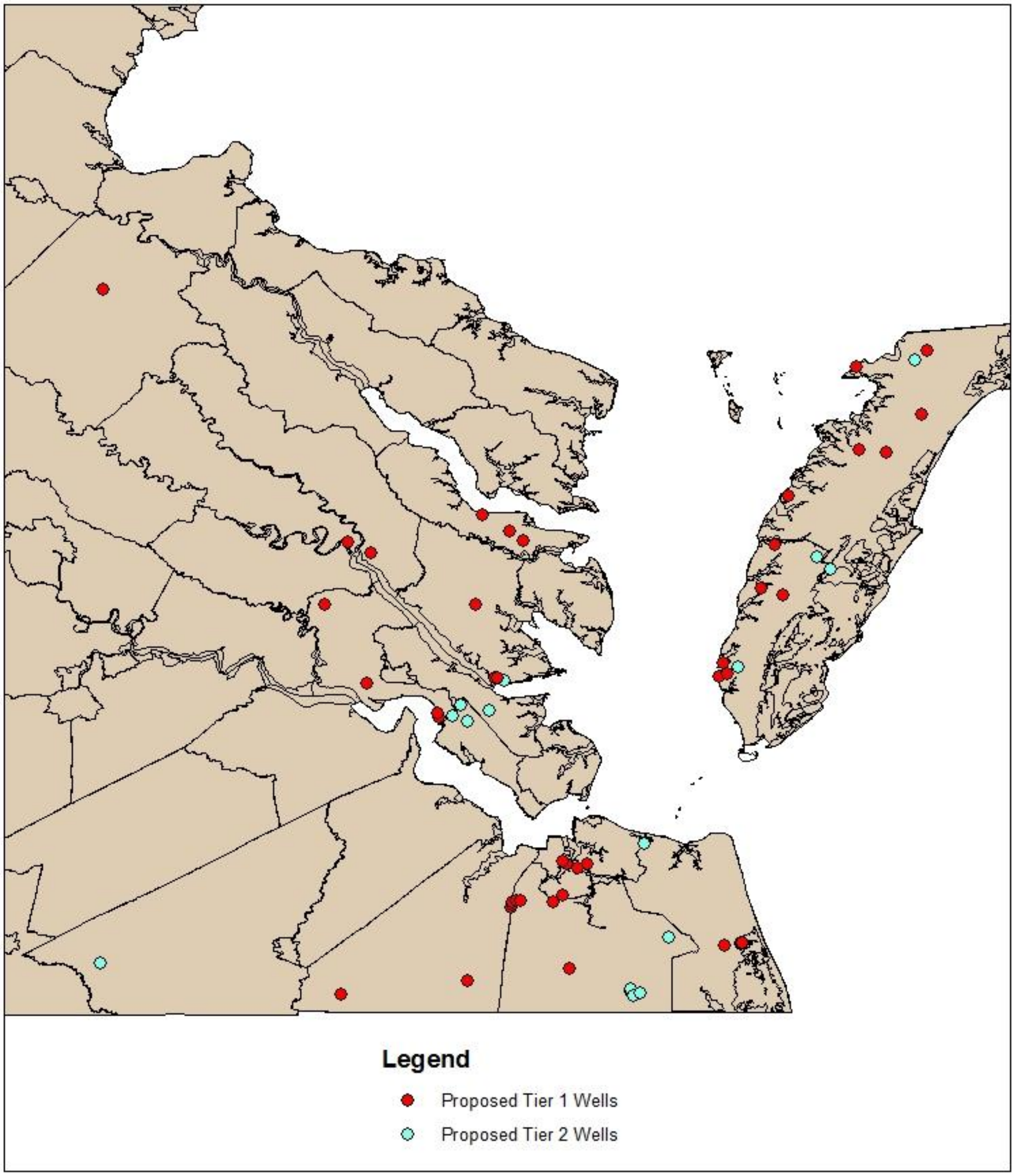


Figure 1 Appendix B: Locations of proposed Tier 1 and Tier 2 chloride monitoring wells.

Table 1 Appendix B: Proposed Tier 1 wells

USGS Local #	Well or Owner Name	DEQ #	USGS SITE ID #	LAT_27	LON_27	Data Source	Date Cl min	Cl min	Date Cl max	Cl max	Delta Cl
					Proposed Tier I Wells						
63J 3	Concords Wharf SOW 113C	165-0199	373230075541003	37.542222	-75.902778	EPA	8/25/1980	27.00	8/7/1986	6400.00	6373
66M 18	Whitams SOW 110C	100-0425	375723075344403	37.956389	-75.578889	EPA	1/23/1979	126.00	10/30/1987	2230.00	2104
59G 22	Gloucester Point San Dist #6	-999999	371537076293101	37.260422	-76.491617	USGS	7/15/1975	10.00	1/16/1980	1700.00	1690
63B 21	-999999	-999999	364147075582601	36.696389	-75.973889	EPA	8/26/1986	10.00	7/26/1988	1500.00	1490
62B 1	Pungo SOW 98A	228-0167	364126076003501	36.690556	-76.009722	EPA	7/25/1979	86.00	8/26/1986	1450.00	1364
59C 41	-999999	-999999	364619076274301	36.771889	-76.462	DEQ	1/13/2005	198.00	10/20/2005	1482.00	1284
65K 23	Bayside SOW 109C	100-0432	374442075432501	37.745	-75.723611	EPA	6/15/1978	2.00	2/1/1988	1260.00	1258
59C 43	-999999	-999999	364638076273801	36.777333	-76.460472	DEQ	10/28/2004	159.00	7/22/2005	1413.00	1254
56A 1	Cleopus SOW 47	161-0047	363511076492901	36.586541	-76.824403	USGS	4/13/1972	3.50	3/22/1972	1200.00	1196.5
58H 2	Town of Gloucester #1	-999999	372458076321401	37.416111	-76.537778	EPA	1/15/1980	2.00	10/16/1979	1070.00	1068
59G 19	Gloucester San Dist #2 Well 2	-999999	371537076290501	37.26	-76.496667	EPA	8/20/1975	11.00	10/16/1979	1070.00	1059
56J 11	Westpoint Airport SOW 73	149-0004	373126076454101	37.523889	-76.761389	EPA	7/10/1985	2.00	6/16/2005	1019.80	1017.8
63B 19	-999999	-999999	364147075583401	36.696389	-75.976111	EPA	6/10/1987	49.60	4/28/1988	963.00	913.4
63B 17	-999999	-999999	364145075583301	36.695833	-75.975833	EPA	8/26/1986	39.00	12/9/1987	930.00	891
65M 3	HV Drewer and Son #1	-999999	375512075434802	37.920222	-75.729917	EPA	8/20/1979	1.00	12/8/1982	870.00	869
60B 4	Fennema SOW 90B	234-0135	363836076201702	36.643484	-76.337719	USGS	8/27/1986	32.00	6/21/2005	876.00	844
63B 20	-999999	-999999	364147075583201	36.696389	-75.975556	EPA	2/4/1986	30.00	10/25/1988	859.00	829
59J 8	Wilton Elementary School	-999999	373304076261801	37.551248	-76.438003	USGS	2/19/1975	28.00	1/16/1980	830.00	802
63B 23	-999999	-999999	364148075583201	36.696667	-75.975556	EPA	9/12/1985	226.00	3/13/1990	990.00	764
63B 22	-999999	-999999	364148075582701	36.696556	-75.974111	EPA	9/12/1985	2.00	6/10/1987	710.00	708
59C 46	-999999	-999999	364708076270101	36.785444	-76.450333	DEQ	4/13/2006	73.00	8/17/2006	747.00	674
58A 81	Dismal Swamp SOW 180E	161-0416	363655076332006	36.615429	-76.555228	USGS	10/20/1986	10.00	2/10/1988	674.00	664
63B 15	-999999	-999999	364142075583401	36.695	-75.976111	EPA	9/12/1985	36.00	6/10/1987	600.00	564
60C 67	-999999	-999999	365147076180601	36.863194	-76.301694	EPA	6/27/1978	8.00	11/14/1983	550.00	542
58J 9	JM Barnhardt #2A	-999999	373622076312101	37.60625	-76.522173	USGS	1/13/1970	8.90	1/13/1970	464.00	455.1
63B 16	-999999	-999999	364143075583301	36.695278	-75.975833	EPA	8/26/1986	32.00	6/10/1987	464.00	432
59C 45	-999999	-999999	364702076273301	36.783944	-76.459194	DEQ	8/17/2006	113.00	7/28/2004	521.00	408
63H 8	Candlelight Lodge	-999999	372620075525501	37.436667	-75.885278	EPA	11/28/1979	10.00	5/22/1978	400.00	390
63B 24	-999999	-999999	364149075583301	36.696944	-75.975833	EPA	5/22/1989	19.00	6/10/1987	384.00	365
64K 9	Hacks Neck SOW 106A	100-0414	373845075522502	37.645833	-75.873611	EPA	8/20/1980	92.00	8/5/1986	450.00	358
65K 29	Perdue SOW 114C	100-0445	374425075400003	37.740278	-75.666667	EPA	2/13/1980	3.00	11/11/1987	360.00	357
58F 16	BASF Deep Well 4	-999999	371530076473001	37.176944	-76.614444	EPA	7/24/1979	7.00	2/3/1976	360.00	353
60C 40	City of Chesapeake TW-1	-999999	364702076215601	36.783444	-76.372222	EPA	3/25/1982	239.00	3/24/1982	585.00	346
59J 34	-999999	-999999	373420076275701	37.572222	-76.465833	EPA	8/16/1977	10.00	10/31/1977	310.00	300
56J 5	West Point Mill Glenn St Old	-999999	373246076483001	37.547083	-76.80875	EPA	1/16/1979	13.00	10/29/1987	307.00	294
62G 29	-999999	-999999	371544076011601	37.26225	-76.021083	DEQ	9/22/1999	226.00	1/5/2006	500.00	274
60C 58	-999999	-999999	364752076210601	36.797778	-76.351667	DEQ	10/26/2006	18.00	12/17/2004	286.00	268
66L 6	Messick and Wessells Laundrymat	-999999	374900075352401	37.818611	-75.59	EPA	11/27/1978	9.00	8/20/1979	273.00	264
60C 71	-999999	-999999	365210076211603	36.869444	-76.354444	DEQ	5/19/2004	240.00	8/21/2006	489.00	249
63B 26	-999999	-999999	364149075582402	36.697083	-75.973417	EPA	1/4/1980	123.00	10/25/1988	320.00	197
63H 4	PC Kellam SOW 103C	165-0146	372705075555901	37.451389	-75.933056	EPA	6/26/1984	246.00	1/28/1988	431.00	185
59C 47	-999999	-999999	364714076263801	36.787083	-76.443972	DEQ	1/13/2005	100.00	4/13/2006	277.00	177
60C 7	Portsmouth PP Sewage Disposal	-999999	365115076191701	36.8545	-76.320833	EPA	6/13/1969	189.00	9/5/1978	365.00	176
62G 16	Bayshore #2 Gate	-999999	371544076011801	37.262083	-76.021861	EPA	5/7/1979	100.00	7/20/1987	269.00	169
56H 25	Diascund SOW 177A	147-0169	372506076511701	37.414313	-76.858852	USGS	8/26/1993	220.00	6/15/2005	381.90	161.9
60C 35	Portsmouth Plant North Well WE-3	-999999	365148076203901	36.863444	-76.344167	EPA	9/23/1981	245.00	5/14/1987	403.00	158
56F 56	-999999	-999999	371453076460601	37.24797	-76.768684	DEQ	6/8/2006	218.00	3/6/2002	352.00	134
58F 22	BASF Deep Well 3	-999999	371525076473001	37.183889	-76.617222	EPA	10/17/1975	209.00	2/3/1976	310.00	101
52N 25	-999999	-999999	380505077194501	38.084722	-77.329167	EPA	7/16/1987	234.00	10/11/1988	294.00	60
62G 30	-999999	-999999	371606076001801	37.268361	-76.004861	DEQ	6/2/2006	242.00	2/15/2006	292.00	50
62G 34	-999999	-999999	371727076004701	37.290722	-76.012944	DEQ	8/26/2004	245.00	6/7/2006	260.00	15

Table 2 Appendix B: Proposed Tier 2 wells

USGS Local #	Well or Owner Name	DEQ #	USGS SITE ID #	LAT_27	LON_27	Data Source	Date Cl min	Cl min	Date Cl max	Cl max	Delta Cl
					Proposed Tier 2 Wells						
61B 12	Fentress SOW 91E	234-0191	364227076074706	36.70765	-76.129379	USGS	7/29/1993	15000.00	4/22/1998	17200.00	2200
66M 25	Jenkins Bridge SOW 181C	100-0563	375610075361803	37.936111	-75.605	EPA	8/29/1988	2100.00	10/30/1987	3500.00	1400
61D 5	Ferry Road SOW 155	228-0162	365425076105001	36.907092	-76.180215	USGS	5/10/1979	8975.00	3/29/2000	10200.00	1225
61A 12	Northwest River NWR-2	-999999	363553076123101	36.598144	-76.208575	DEQ	11/19/2004	2562.00	7/2/2004	3786.00	1224
58A 77	Dismal Swamp SOW 180A	161-0412	363655076332002	36.615278	-76.555556	EPA	8/10/1993	1600.00	2/17/1988	2600.00	1000
61A 5	City of Chesapeake TW-2	-999999	363535076123601	36.593	-76.209917	EPA	4/16/1982	310.00	4/17/1982	1295.00	985
66M 23	Jenkins Bridge SOW 181A	100-0561	375610075361801	37.936111	-75.605	EPA	8/29/1988	1500.00	10/29/1987	2380.00	880
64H 5	Oceanside SOW 102C	100-0399	372922076470101	37.490278	-75.784444	EPA	3/1/1989	2000.00	11/12/1987	2880.00	880
62B 2	Pungo SOW 98B	228-0168	364126076003502	36.690556	-76.009722	EPA	8/6/1981	1295.00	2/25/1982	2160.00	865
58F 50	Newport News Park SOW 171A	216-0018	371208076341101	37.202368	-76.569397	USGS	6/19/1984	2000.00	9/29/1983	2850.00	850
58F 87	Lee Hall 3 UPPW	-999999	371000076331602	37.166722	-76.554383	DEQ	8/30/2005	1324.00	6/22/2005	2115.00	791
58F 86	Lee Hall 3 MPPW	-999999	371000076331601	37.1666	-76.554417	DEQ	3/2/2005	1477.00	1/27/2004	2214.00	737
64J 11	Willis Wharf SOW 112C	165-0194	373059075484503	37.516389	-75.8125	EPA	8/21/1980	1510.00	11/10/1987	2210.00	700
63B 25	-999999	-999999	364149075582401	36.696944	-75.973333	EPA	2/14/1989	79.00	7/26/1988	762.00	683
61A 19	Northwest River NWR OW-5	-999999	363527076112001	36.591333	-76.188611	DEQ	3/17/1999	3180.00	4/8/2005	3847.00	667
58F 82	Lee Hall 3-7 MPMW	-999999	371130076303601	37.191534	-76.510229	USGS	5/19/1995	2000.00	5/14/1995	2600.00	600
63G 24	Cheriton SOW 111C	165-0190	371653075584803	37.281389	-75.98	EPA	6/29/1979	383.00	11/10/1987	905.00	522
66M 26	Jenkins Bridge SOW 181D	100-0564	375610075361804	37.936111	-75.605	EPA	8/29/1988	810.00	10/30/1987	1310.00	500
61A 13	Northwest River NWR-3	-999999	363506076121301	36.58495	-76.203567	DEQ	7/25/2005	3601.00	4/8/2005	4098.00	497
61B 13	Fentress SOW 91F	234-0192	364227076074707	36.70765	-76.129379	USGS	7/30/1993	4600.00	4/22/1997	5060.00	460
59G 12	Theodore Pratt #1	-999999	371511076284201	37.253194	-76.478556	EPA	2/19/1975	870.00	8/25/1976	1300.00	430
58F 89	Lee Hall 1 MPPW	-999999	371041076351703	37.178389	-76.588197	DEQ	4/26/2005	1738.00	3/2/2005	2025.00	287
60C 69	-999999	-999999	365210076211601	36.869444	-76.354444	DEQ	6/26/2006	637.00	11/16/2004	924.00	287
52B 9	Little Texas SOW 178B	187-0181	363916077201002	36.654595	-77.335806	USGS	7/25/1985	443.00	10/1/1985	720.00	277

(*Well 63B 25 is in Tier 2 even though the most recent sample had an unusually low chloride concentration that makes it appear to fit Tier 1 conditions).

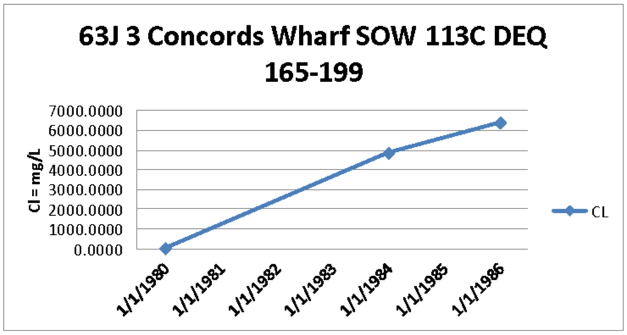
Table 3 Appendix B: Evaluated Mainland Coastal Plain Tier 1 and Tier 2 wells

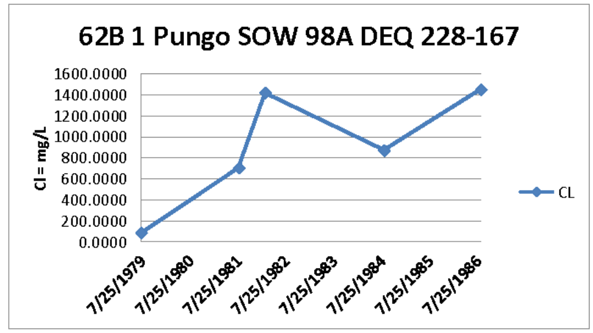
USGS Local #	Well or Owner Name	DEQ #	EVALUATION REMARKS
Mainland Tier 1 Wells			
56H 25	Diascund SOW 177A	147-0169	REMAIN Tier 1
52N 25	Fort AP Hill Picnic Area	116-0383	REMAIN Tier 1
62B 1	Pungo SOW 98A	228-0167	REMAIN - disregarding extremely low initial sample **drops well to Tier 2 below**
60C 40	City of Chesapeake TW-1	234-0174	Additional well construction data needed for evaluation - very likely multi screened
60C 58	National Linen Service Well 1	220-0049	Additional info needed - listed as multi-screened well 655-665 and 665-695
59G 19	Gloucester San Dist #2 Well 2	136-0026	**ELIMINATED** - multi-screened well near York River
60C 71	Cognetrix Well C	220-0042	**ELIMINATED** - multi-screened well
60C 7	Portsmouth Pinners Point SOW 194	220-0004	**ELIMINATED** - multi-screened well
56F 56	James City Srvc Auth BGD-2	147-0294	**ELIMINATED** - multi-screened well
60C 35	Portsmouth Plant North Well WE-3	220-0003	**ELIMINATED** - large diameter screen 72 feet in length
58F 16	BASF Deep Well 4	147-0010	**ELIMINATED** - multi-screened well
58F 22	BASF Deep Well 3	147-0009	**ELIMINATED** - multi-screened well
59G 22	Gloucester Point San Dist #6	136-0037	**ELIMINATED** - disregarding extremely low initial sample eliminates well from Tier 1 and 2
63B 21	Meiggs Hog Farm	228-0375	**ELIMINATED** - shallow well for monitoring CAFO manure lagoon
59C 41	Chesapeake Westrn Brnch MW-6	234-0216	**ELIMINATED** - multi-screened well
59C 43	Chesapeake Westrn Brnch MW-2	234-0256	**ELIMINATED** - multi-screened well
56A 1	Cleopus SOW 47	161-0047	**ELIMINATED** - Data is highly variable with extreme fluctuations
58H 2	Town of Gloucester #1	136-0027	**ELIMINATED** - disregarding 4 extremely low & high data points eliminates well from Tier 1 & 2
56J 11	Westpoint Airport SOW 73	149-0004	**ELIMINATED** - disregarding 2 extremely low data points eliminates well from Tier 1 and 2
63B 19	Meiggs Hg Frm New Lagoon W Brm	228-0340	**ELIMINATED** - shallow well for monitoring CAFO manure lagoon
63B 17	Meiggs Hg Frm New Lagoon S Brm	228-0342	**ELIMINATED** - shallow well for monitoring CAFO manure lagoon
60B 4	Fennema SOW 90B	234-0135	**ELIMINATED** - disregarding extremely low sample eliminates well from Tier 1 and 2
63B 20	Meiggs Hg Frm New Lagoon E Brm	228-0341	**ELIMINATED** - shallow well for monitoring CAFO manure lagoon
63B 23	Meiggs Hg Frm New Lagoon N	228-0329	**ELIMINATED** - shallow well for monitoring CAFO manure lagoon
59J 8	Wilton Elementary School	159-0047	**ELIMINATED** - disregard extremely high sample likely from a different well per note in paper file
63B 22	Meiggs Hg Frm South MW 5	228-0134	**ELIMINATED** - shallow well for monitoring CAFO manure lagoon
59C 46	Chesapeake Westrn Brnch MW-5	234-0209	**ELIMINATED** - multi-screened well
58A 81	Dismal Swamp SOW 180E	161-0416	**ELIMINATED** - disregarding low initial air lifted sample eliminates well from Tier 1 and 2
63B 15	Meiggs Hg Frm New Lagoon W	228-0330	**ELIMINATED** - shallow well for monitoring CAFO manure lagoon
60C 67	Norfolk General Hospital	217-0002	**ELIMINATED** - disregarding 3 extremely low samples eliminates well from Tier 1 and 2
58J 9	JM Barnhardt #2A	159-0004	**ELIMINATED** - very limited data that is highly variable
63B 16	Meiggs Hg Frm New Lagoon S	228-0332	**ELIMINATED** - shallow well for monitoring CAFO manure lagoon
59C 45	Chesapeake Westrn Brnch MW-3	234-0257	**ELIMINATED** - multi-screened well
63B 24	Meiggs Hg Frm New Lagoon N Brm	228-0339	**ELIMINATED** - shallow well for monitoring CAFO manure lagoon
59J 34	HL Revere Bottle Gas at Trailer Crt	159-0065	**ELIMINATED** - disregarding extremely low initial sample eliminates well from Tier 1 and 2
56J 5	West Point Mill Glenn St Old	150-0001	**ELIMINATED** - well recently abandoned
63B 26	Meiggs Hog Farm North MW	228-0060	**ELIMINATED** - shallow well for monitoring CAFO manure lagoon
59C 47	Chesapeake Westrn Brnch MW-1	234-0210	**ELIMINATED** - multi-screened well
Mainland Tier 2 Wells			
61B 12	Fentress SOW 91E	234-0191	REMAIN Tier 2
61D 5	Ferry Road SOW 155	228-0162	REMAIN Tier 2
62B 2	Pungo SOW 98B	228-0168	REMAIN Tier 2
58F 50	Newport News Park SOW 171A	216-0018	REMAIN Tier 2 (well condition currently under evaluation via packer test)
62B 1	Pungo SOW 98A	228-0167	REMAIN but becomes Tier 2 - disregarding extremely low initial sample drops well to **Tier 2**
61B 13	Fentress SOW 91F	234-0192	REMAIN Tier 2
61A 5	City of Chesapeake TW-2	234-0175	Additional well construction data needed for evaluation - very likely multi screened
58F 89	Lee Hall 1 MPPW	216-0040	**ELIMINATED** - (2 screens listed 1017 to 1126 and 1126 to 1131 for a total of 114 feet)
58F 82	Lee Hall 3-7 MPMW	199-0107	**ELIMINATED** - multi-screened well (formerly known as 216-00046)
61A 12	Northwest River NWR-2	234-0221	**ELIMINATED** - multi-screened well
61A 19	Northwest River NWR OW-5	234-0226	**ELIMINATED** - multi-screened well
61A 13	Northwest River NWR-3	234-0222	**ELIMINATED** - multi-screened well
58A 77	Dismal Swamp SOW 180A	161-0412	**ELIMINATED** - disregarding extremely high value of split sample eliminates well from Tier 1 & 2
58F 87	Lee Hall 3 UPPW	216-0037	**ELIMINATED** - multi-screened well
58F 86	Lee Hall 3 MPPW	216-0042	**ELIMINATED** - multi-screened well
63B 25	Meiggs Hog Farm	228-0374	**ELIMINATED** - shallow well for monitoring CAFO manure lagoon
59G 12	Theodore Pratt #1 (destroyed)	136-0020	**ELIMINATED** - well destroyed
60C 69	Cogentrix Well A (abandoned)	220-0040	**ELIMINATED** - well abandoned
52B 9	Little Texas SOW 178B (failed well)	187-0181	**ELIMINATED** - well did not recover after last pumped

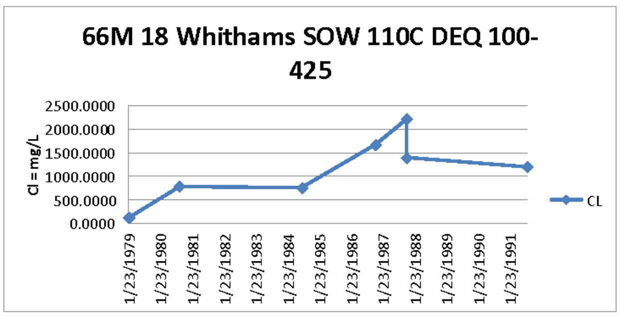
Table 4 Appendix B: Evaluated Eastern Shore Coastal Plain Tier 1 and Tier 2 wells

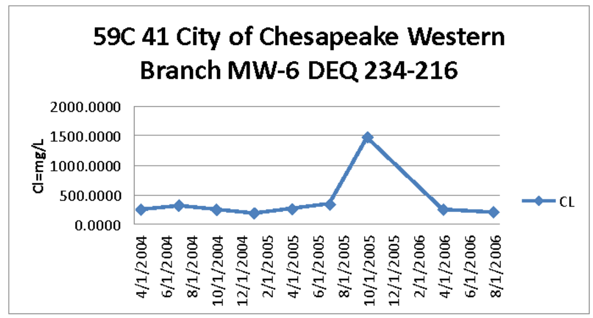
USGS Local #	Well or Owner Name	DEQ #	EVALUATION REMARKS
Eastern Shore Tier 1 Wells			
65M 3	HV Drewer and Son #1	100-0237	REMAIN Tier 1
62G 29	Bayshore Well 7	165-0389	REMAIN Tier 1
62G 16	Bayshore #2 Gate	165-0110	REMAIN Tier 1
62G 30	Cape Charles Tower Well	165-0387	REMAIN Tier 1
62G 34	Cherrystone Campground Well 8	165-0096	REMAIN Tier 1
64K 9	Hacks Neck SOW 106A	100-0414	**ELIMINATED** - (37 feet deep, screen 17-37, grout 0-15, gravel 15-37, innundated by Hurricane Floyd)
63J 3	Concords Wharf SOW 113C	165-0199	**ELIMINATED** - hole depth overdrilled below screen resulting in potential upconing
66M 18	Whitams SOW 110C	100-0425	**ELIMINATED** - conductivity declines during pumping and will not stabilize for sampling
65K 23	Bayside SOW 109C	100-0432	**ELIMINATED** - hole depth overdrilled below screen resulting in potential upconing
63H 8	Candlelight Lodge	165-0057	**ELIMINATED** - Samples note change in Cl is a decrease to nearly 0
65K 29	Perdue SOW 114C	100-0445	**ELIMINATED** - hole depth overdrilled below screen resulting in potential upconing
66L 6	Messick and Wessells Laundrymat	100-0019	**ELIMINATED** - single data point exceeds 250 mg/L, all others below 15 mg/L
63H 4	PC Kellam SOW 103C	165-0146	**ELIMINATED** - hole depth overdrilled below screen resulting in potential upconing
Eastern Shore Tier 2 Wells			
66M 25	Jenkins Bridge SOW 181C	100-0563	REMAIN Tier 2
66M 23	Jenkins Bridge SOW 181A	100-0561	REMAIN Tier 2
66M 26	Jenkins Bridge SOW 181D	100-0564	REMAIN Tier 2
64H 5	Oceanside SOW 102C	100-0399	**ELIMINATED** - hole depth overdrilled below screen resulting in potential upconing
64J 11	Willis Wharf SOW 112C	165-0194	**ELIMINATED** - hole depth overdrilled below screen resulting in potential upconing
63G 24	Cheriton SOW 111C	165-0190	**ELIMINATED** - hole depth overdrilled below screen resulting in potential upconing

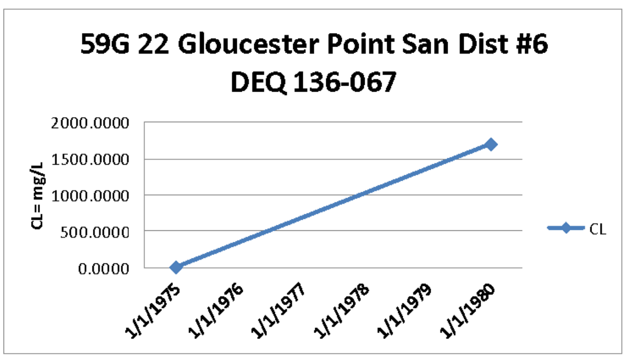
Proposed Tier 1 Wells Chloride Data Plots

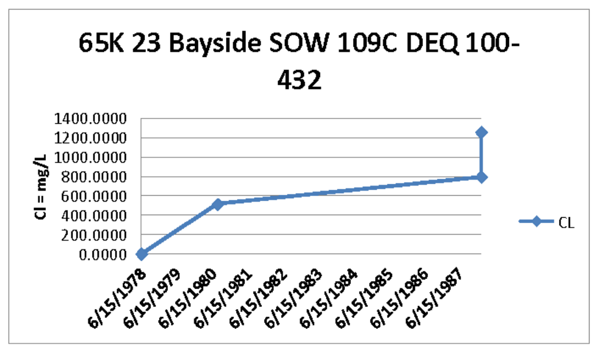

63J 3 Concords Wharf SOW 113C DEQ 165-199
Cl = mg/L
7000.0000
6000.0000
5000.0000
4000.0000
3000.0000
2000.0000
1000.0000
0.0000
1/1/1980
1/1/1981
1/1/1982
1/1/1983
1/1/1984
1/1/1985
1/1/1986
CL

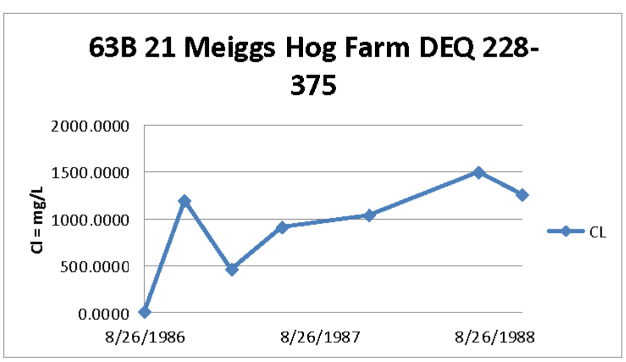

62B 1 Pungo SOW 98A DEQ 228-167
Cl = mg/L
1600.0000
1400.0000
1200.0000
1000.0000
800.0000
600.0000
400.0000
200.0000
0.0000
7/25/1979
7/25/1980
7/25/1981
7/25/1982
7/25/1983
7/25/1984
7/25/1985
7/25/1986
CL

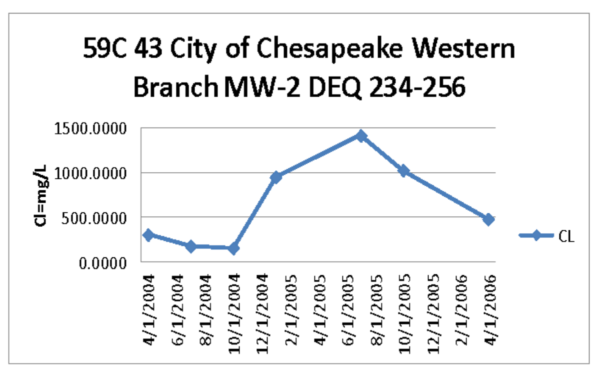

66M 18 Whithams SOW 110C DEQ 100-425
Cl = mg/L
2500.0000
2000.0000
1500.0000
1000.0000
500.0000
0.0000
1/23/1979
1/23/1980
1/23/1981
1/23/1982
1/23/1983
1/23/1984
1/23/1985
1/23/1986
1/23/1987
1/23/1988
1/23/1989
1/23/1990
1/23/1991
CL

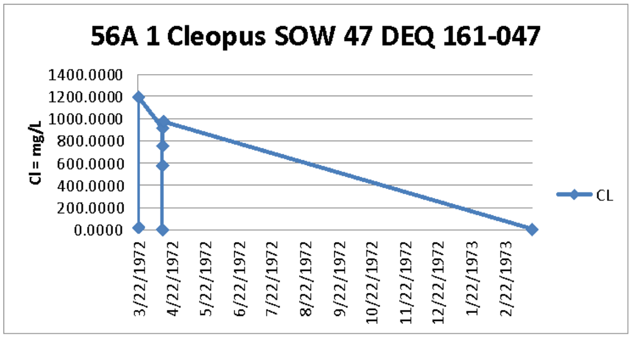

59C 41 City of Chesapeake Western Branch MW-6 DEQ 234-216
Cl=mg/L
2000.0000
1500.0000
1000.0000
500.0000
0.0000
4/1/2004
6/1/2004
8/1/2004
10/1/2004
12/1/2004
2/1/2005
4/1/2005
6/1/2005
8/1/2005
10/1/2005
12/1/2005
2/1/2006
4/1/2006
6/1/2006
8/1/2006
CL


59G 22 Gloucester Point San Dist #6 DEQ 136-067
Cl = mg/L
2000.0000
1500.0000
1000.0000
500.0000
0.0000
1/1/1975
1/1/1976
1/1/1977
1/1/1978
1/1/1979
1/1/1980
CL


65K 23 Bayside SOW 109C DEQ 100-432
Cl = mg/L
1400.0000
1200.0000
1000.0000
800.0000
600.0000
400.0000
200.0000
0.0000
6/15/1978
6/15/1979
6/15/1980
6/15/1981
6/15/1982
6/15/1983
6/15/1984
6/15/1985
6/15/1986
6/15/1987
CL


63B 21 Meiggs Hog Farm DEQ 228-375
Cl = mg/L
2000.0000
1500.0000
1000.0000
500.0000
0.0000
8/26/1986
8/26/1987
8/26/1988
CL


59C 43 City of Chesapeake Western Branch MW-2 DEQ 234-256
Cl=mg/L
1500.0000
1000.0000
500.0000
0.0000
4/1/2004
6/1/2004
8/1/2004
10/1/2004
12/1/2004
2/1/2005
4/1/2005
6/1/2005
8/1/2005
10/1/2005
12/1/2005
2/1/2006
4/1/2006
CL


56A 1 Cleopus SOW 47 DEQ 161-047
Cl = mg/L
CL
3/22/1972
4/22/1972
5/22/1972
6/22/1972
7/22/1972
8/22/1972
9/22/1972
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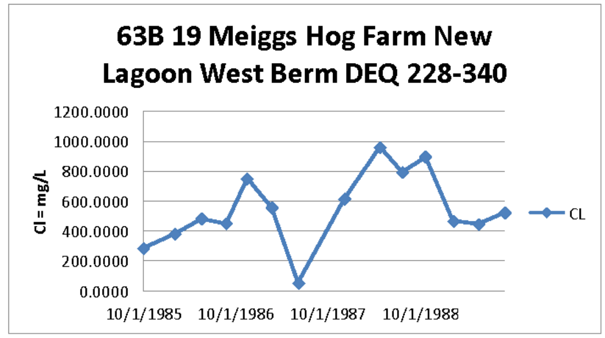
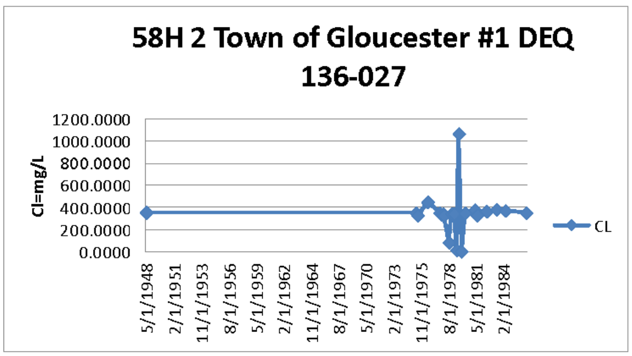
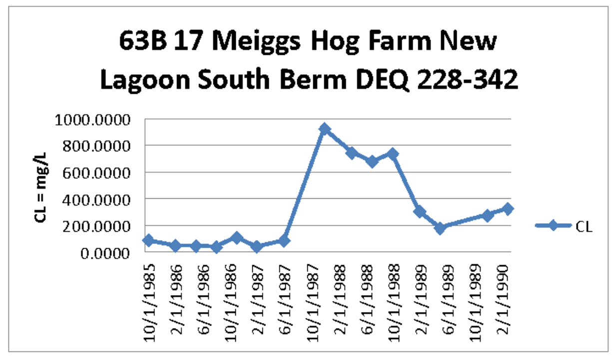
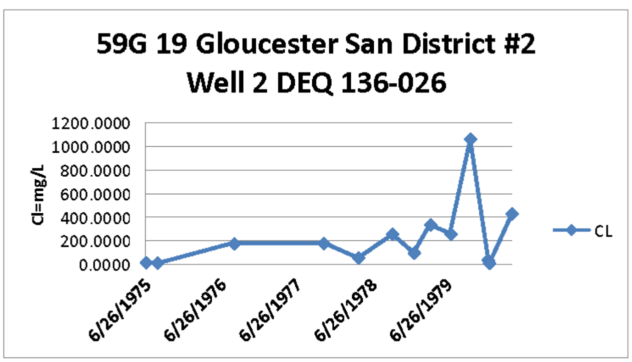
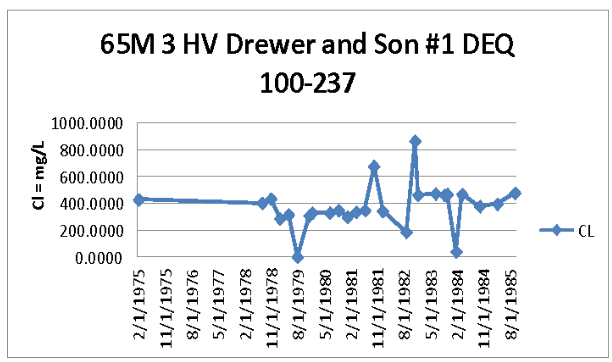
11/22/1972
12/22/1972
1/22/1973
2/22/1973

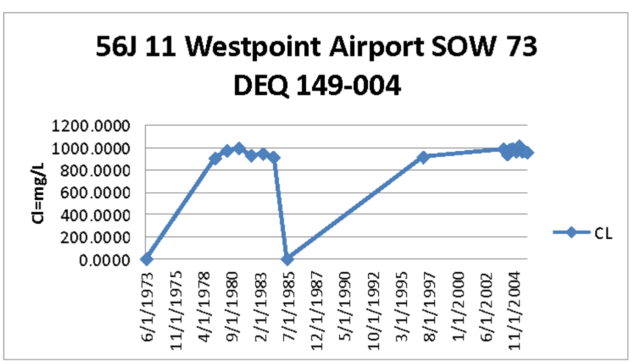

63B 19 Meiggs Hog Farm New Lagoon West Berm DEQ 228-340
Cl = mg/L
CL
10/1/1985
10/1/1986
10/1/1987
10/1/1988

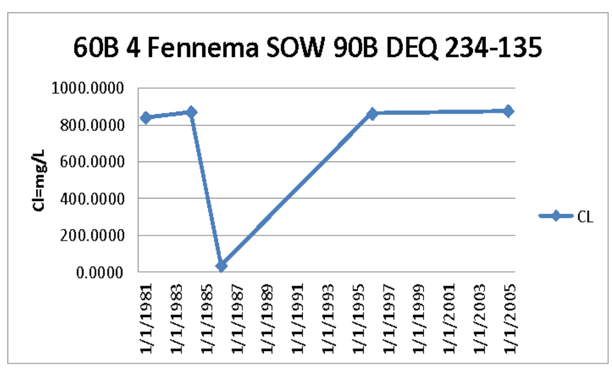

58H 2 Town of Gloucester #1 DEQ 136-027
Cl=mg/L
CL

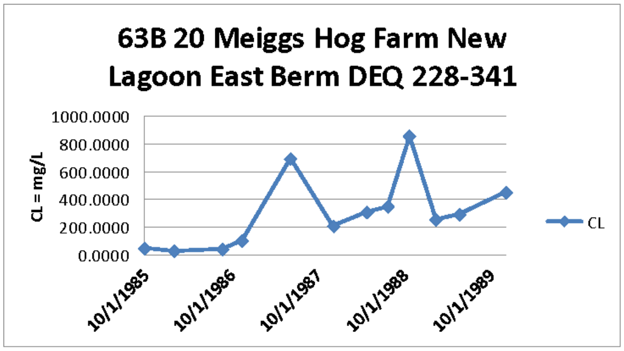

63B 17 Meiggs Hog Farm New Lagoon South Berm DEQ 228-342
Cl = mg/L
CL

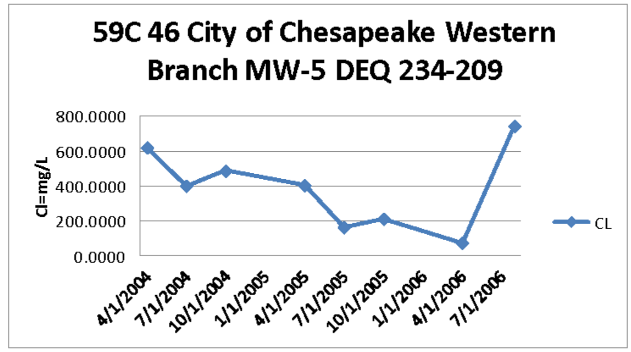

59G 19 Gloucester San District #2 Well 2 DEQ 136-026
Cl=mg/L
CL
6/26/1975
6/26/1976
6/26/1977
6/26/1978
6/26/1979

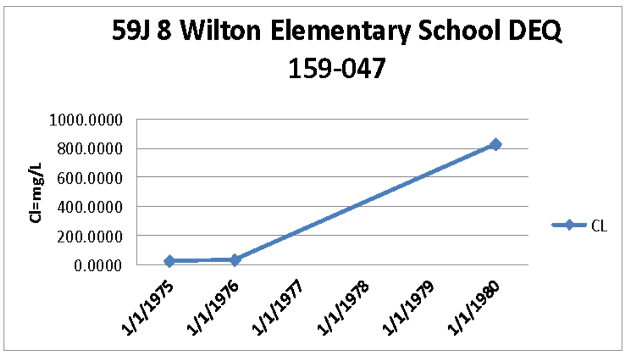

65M 3 HV Drewer and Son #1 DEQ 100-237
Cl = mg/L
CL

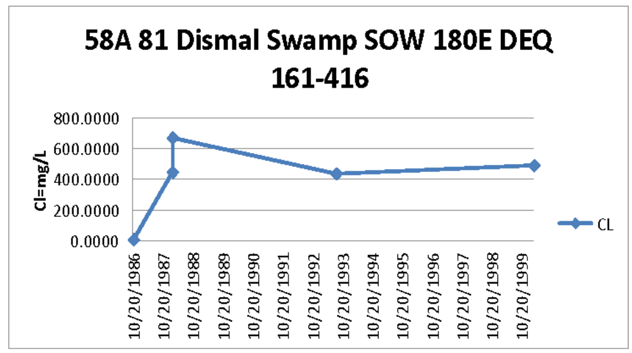

56J 11 Westpoint Airport SOW 73 DEQ 149-004
Cl=mg/L
CL

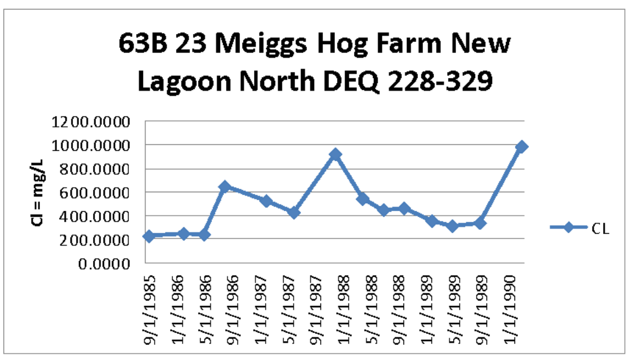

60B 4 Fennema SOW 90B DEQ 234-135
Cl=mg/L
CL

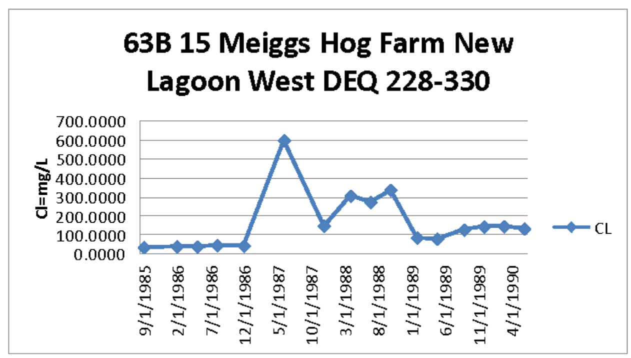

63B 20 Meiggs Hog Farm New Lagoon East Berm DEQ 228-341
CL = mg/L
1000.0000
800.0000
600.0000
400.0000
200.0000
0.0000
10/1/1985
10/1/1986
10/1/1987
10/1/1988
10/1/1989
CL

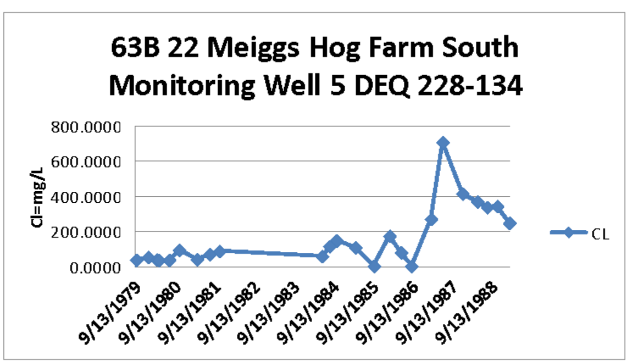

59C 46 City of Chesapeake Western Branch MW-5 DEQ 234-209
Cl=mg/L
800.0000
600.0000
400.0000
200.0000
0.0000
4/1/2004
7/1/2004
10/1/2004
1/1/2005
4/1/2005
7/1/2005
10/1/2005
1/1/2006
4/1/2006
7/1/2006
CL

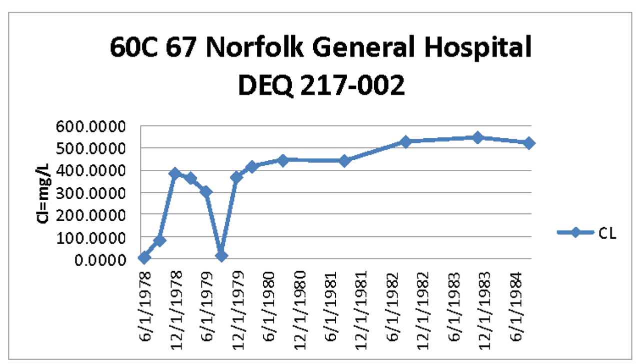

59J 8 Wilton Elementary School DEQ 159-047
Cl=mg/L
1000.0000
800.0000
600.0000
400.0000
200.0000
0.0000
1/1/1975
1/1/1976
1/1/1977
1/1/1978
1/1/1979
1/1/1980
CL

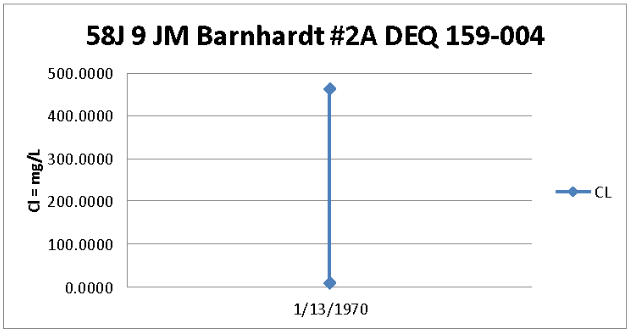

58A 81 Dismal Swamp SOW 180E DEQ 161-416
Cl=mg/L
800.0000
600.0000
400.0000
200.0000
0.0000
10/20/1986
10/20/1987
10/20/1988
10/20/1989
10/20/1990
10/20/1991
10/20/1992
10/20/1993
10/20/1994
10/20/1995
10/20/1996
10/20/1997
10/20/1998
10/20/1999
CL

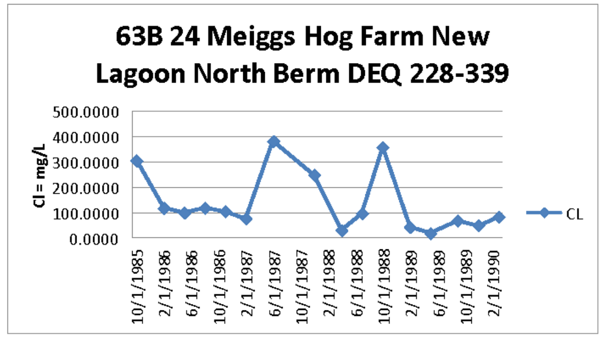

63B 23 Meiggs Hog Farm New Lagoon North DEQ 228-329
Cl=mg/L
1200.0000
1000.0000
800.0000
600.0000
400.0000
200.0000
0.0000
9/1/1985
1/1/1986
5/1/1986
9/1/1986
1/1/1987
5/1/1987
9/1/1987
1/1/1988
5/1/1988
9/1/1988
1/1/1989
5/1/1989
9/1/1989
1/1/1990
CL

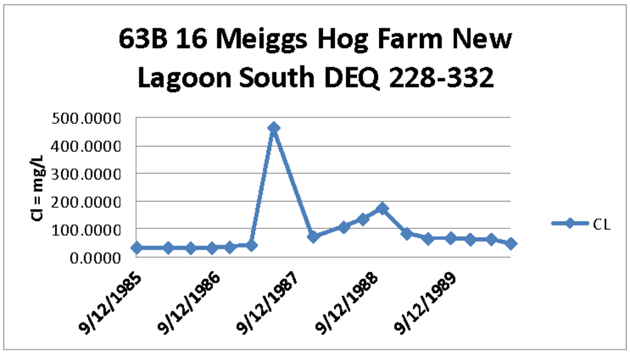

63B 15 Meiggs Hog Farm New Lagoon West DEQ 228-330
Cl=mg/L
700.0000
600.0000
500.0000
400.0000
300.0000
200.0000
100.0000
0.0000
9/1/1985
2/1/1986
7/1/1986
12/1/1986
5/1/1987
10/1/1987
3/1/1988
8/1/1988
1/1/1989
6/1/1989
11/1/1989
4/1/1990
CL

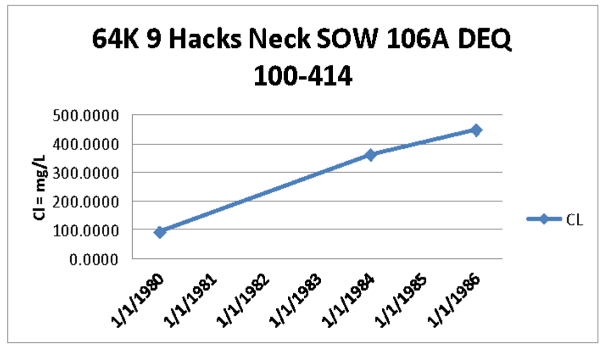

63B 22 Meiggs Hog Farm South Monitoring Well 5 DEQ 228-134
Cl=mg/L
800.0000
600.0000
400.0000
200.0000
0.0000
9/13/1979
9/13/1980
9/13/1981
9/13/1982
9/13/1983
9/13/1984
9/13/1985
9/13/1986
9/13/1987
9/13/1988
CL

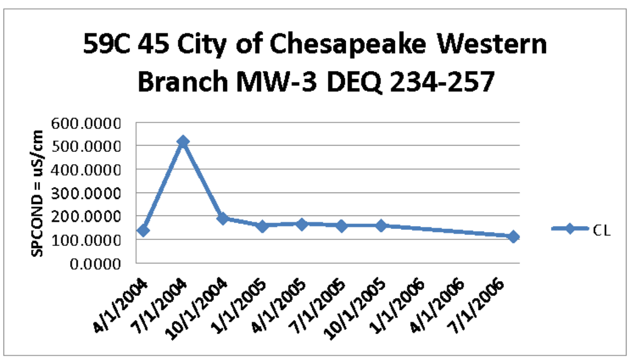

60C 67 Norfolk General Hospital DEQ 217-002
Cl=mg/L
600.0000
500.0000
400.0000
300.0000
200.0000
100.0000
0.0000
6/1/1978
12/1/1978
6/1/1979
12/1/1979
6/1/1980
12/1/1980
6/1/1981
12/1/1981
6/1/1982
12/1/1982
6/1/1983
12/1/1983
6/1/1984
CL

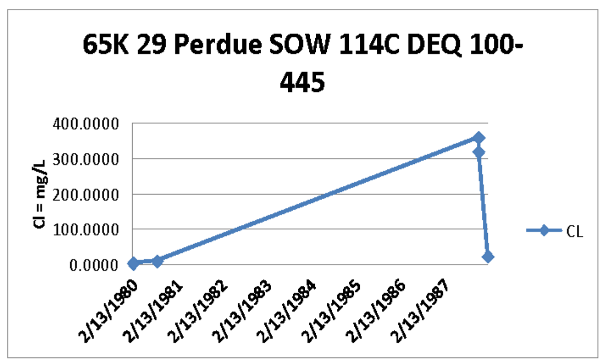

58J 9 JM Barnhardt #2A DEQ 159-004
Cl = mg/L
CL
1/13/1970

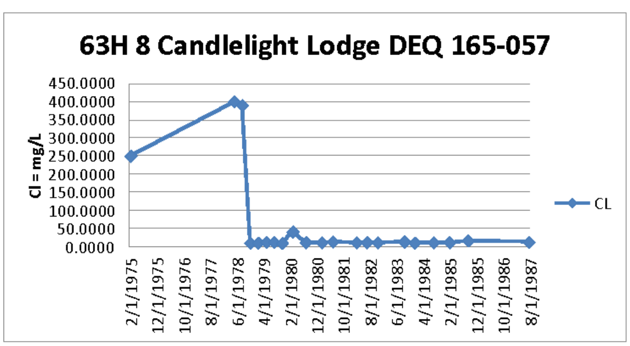

63B 24 Meiggs Hog Farm New Lagoon North Berm DEQ 228-339
Cl = mg/L
CL

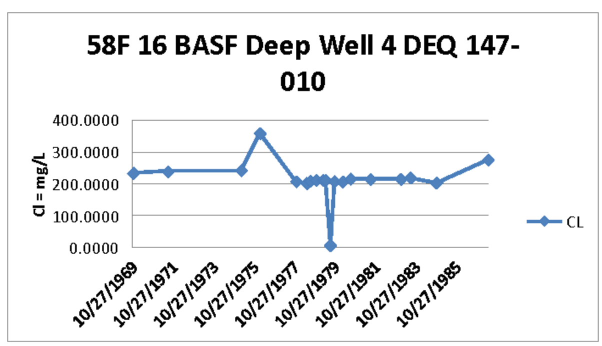

63B 16 Meiggs Hog Farm New Lagoon South DEQ 228-332
Cl = mg/L
CL

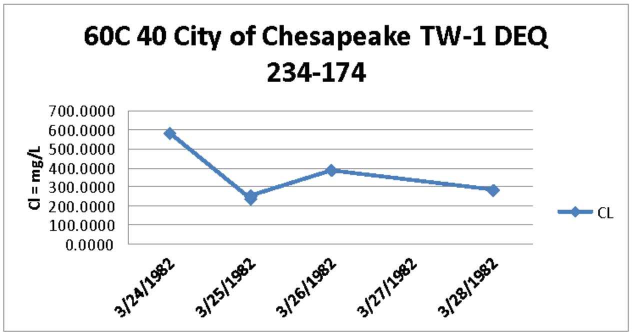

64K 9 Hacks Neck SOW 106A DEQ 100-414
Cl = mg/L
CL

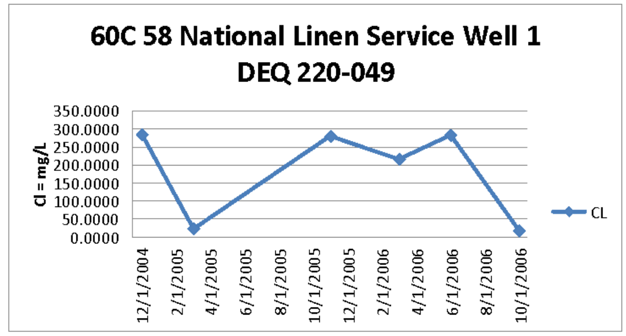

59C 45 City of Chesapeake Western Branch MW-3 DEQ 234-257
SPCOND = uS/cm
CL

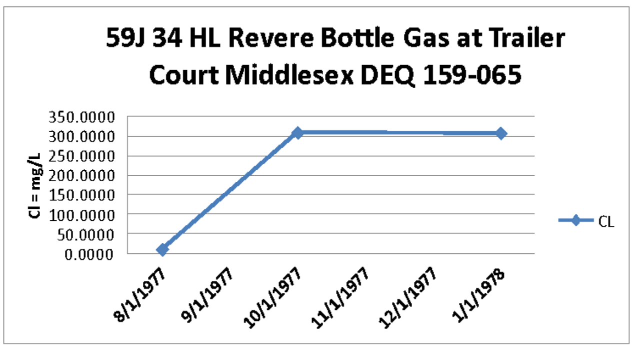

65K 29 Perdue SOW 114C DEQ 100-445
Cl = mg/L
CL

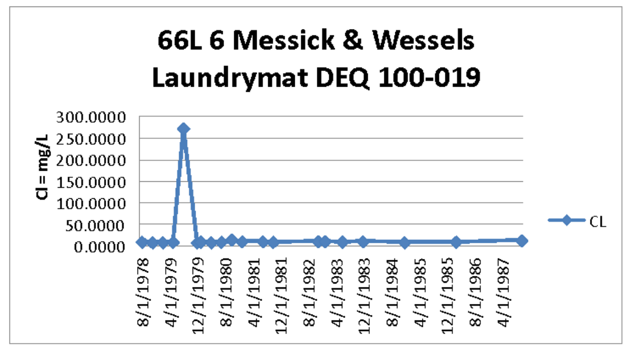

63H 8 Candlelight Lodge DEQ 165-057
Cl = mg/L
CL

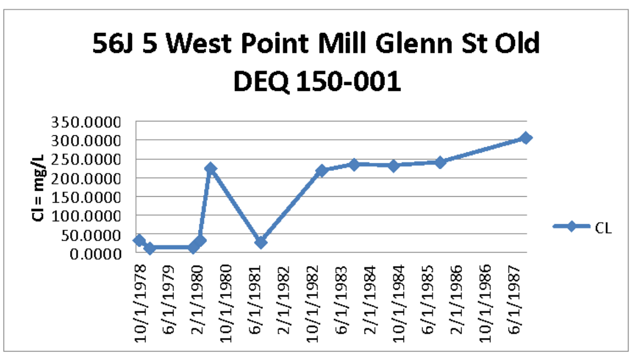

58F 16 BASF Deep Well 4 DEQ 147-010
Cl = mg/L
CL

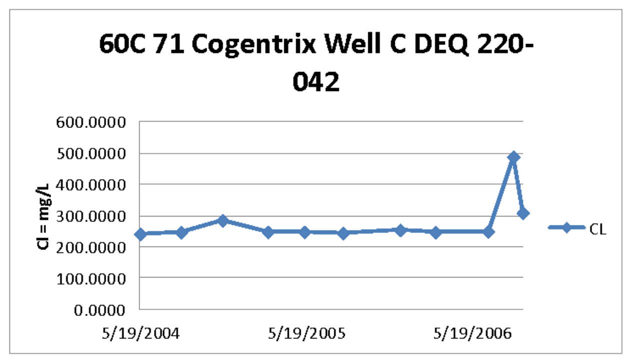

60C 40 City of Chesapeake TW-1 DEQ 234-174
700.0000
600.0000
500.0000
400.0000
300.0000
200.0000
100.0000
0.0000
Cl = mg/L
3/24/1982
3/25/1982
3/26/1982
3/27/1982
3/28/1982
CL

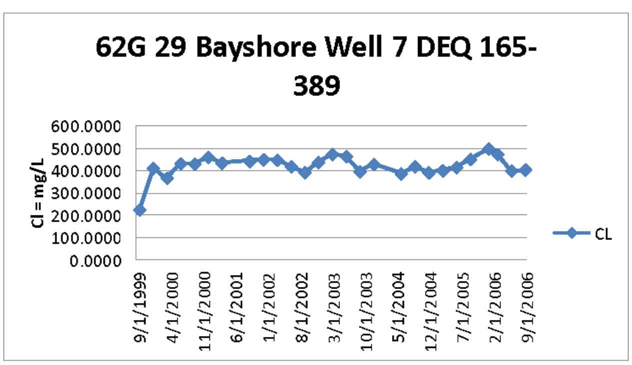

60C 58 National Linen Service Well 1 DEQ 220-049
350.0000
300.0000
250.0000
200.0000
150.0000
100.0000
50.0000
0.0000
Cl = mg/L
12/1/2004
2/1/2005
4/1/2005
6/1/2005
8/1/2005
10/1/2005
12/1/2005
2/1/2006
4/1/2006
6/1/2006
8/1/2006
10/1/2006
CL

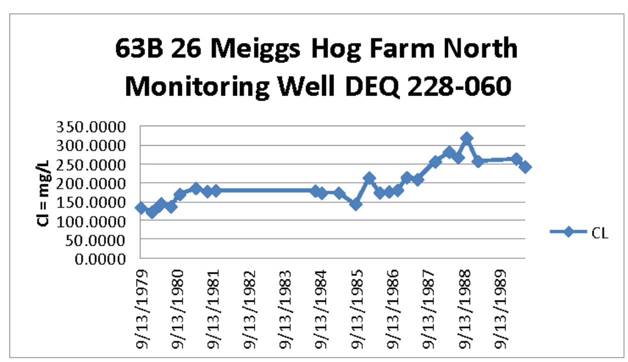

59J 34 HL Revere Bottle Gas at Trailer Court Middlesex DEQ 159-065
350.0000
300.0000
250.0000
200.0000
150.0000
100.0000
50.0000
0.0000
Cl = mg/L
8/1/1977
9/1/1977
10/1/1977
11/1/1977
12/1/1977
1/1/1978
CL

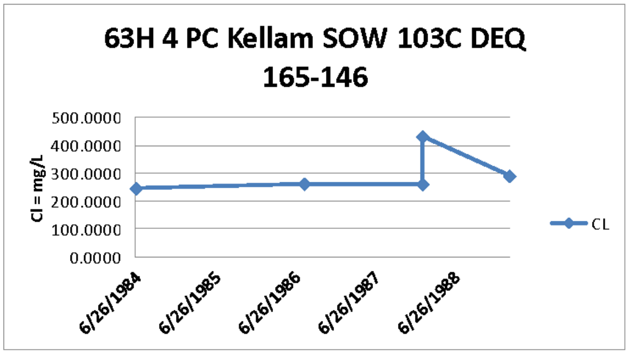

66L 6 Messick & Wessels Laundrymat DEQ 100-019
300.0000
250.0000
200.0000
150.0000
100.0000
50.0000
0.0000
Cl = mg/L
8/1/1978
4/1/1979
12/1/1979
8/1/1980
4/1/1981
12/1/1981
8/1/1982
4/1/1983
12/1/1983
8/1/1984
4/1/1985
12/1/1985
8/1/1986
4/1/1987
CL

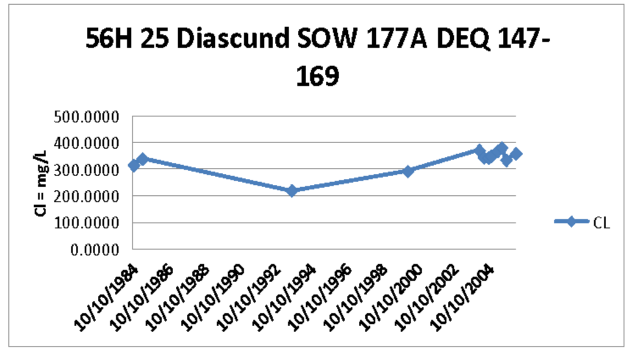

56J 5 West Point Mill Glenn St Old DEQ 150-001
350.0000
300.0000
250.0000
200.0000
150.0000
100.0000
50.0000
0.0000
Cl = mg/L
10/1/1978
6/1/1979
2/1/1980
10/1/1980
6/1/1981
2/1/1982
10/1/1982
6/1/1983
2/1/1984
10/1/1984
6/1/1985
2/1/1986
10/1/1986
6/1/1987
CL

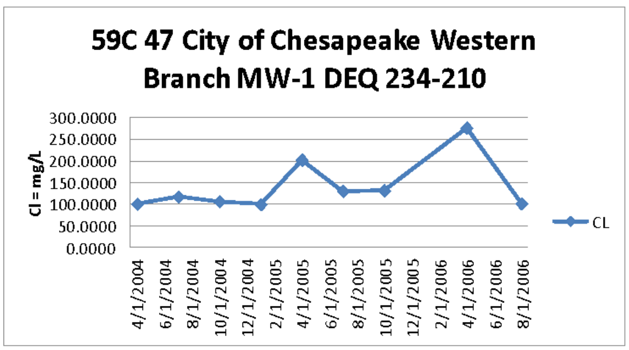

60C 71 Cogentrix Well C DEQ 220-042
600.0000
500.0000
400.0000
300.0000
200.0000
100.0000
0.0000
Cl = mg/L
5/19/2004
5/19/2005
5/19/2006
CL

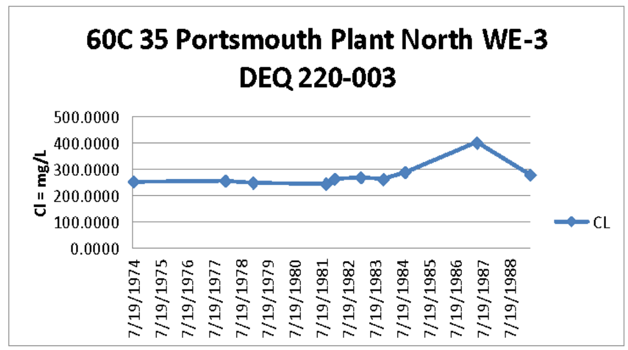

62G 29 Bayshore Well 7 DEQ 165-389
600.0000
500.0000
400.0000
300.0000
200.0000
100.0000
0.0000
Cl = mg/L
9/1/1999
4/1/2000
11/1/2000
6/1/2001
1/1/2002
8/1/2002
3/1/2003
10/1/2003
5/1/2004
12/1/2004
7/1/2005
2/1/2006
9/1/2006
CL

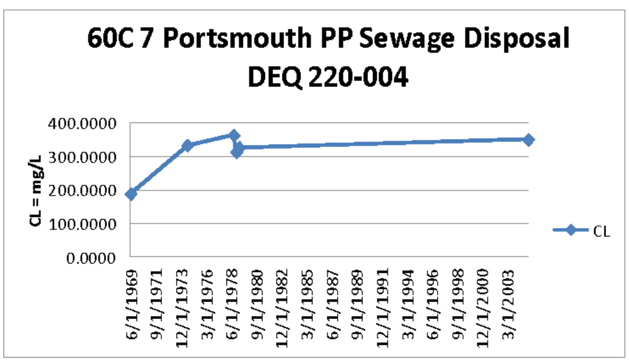

63B 26 Meiggs Hog Farm North Monitoring Well DEQ 228-060
350.0000
300.0000
250.0000
200.0000
150.0000
100.0000
50.0000
0.0000
Cl = mg/L
9/13/1979
9/13/1980
9/13/1981
9/13/1982
9/13/1983
9/13/1984
9/13/1985
9/13/1986
9/13/1987
9/13/1988
9/13/1989
CL

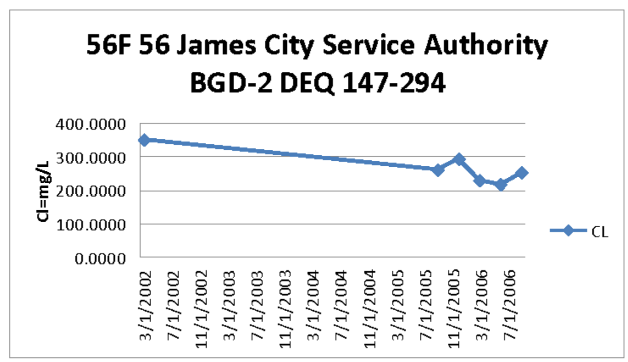

63H 4 PC Kellam SOW 103C DEQ 165-146
Cl = mg/L
500.0000
400.0000
300.0000
200.0000
100.0000
0.0000
6/26/1984
6/26/1985
6/26/1986
6/26/1987
6/26/1988
CL

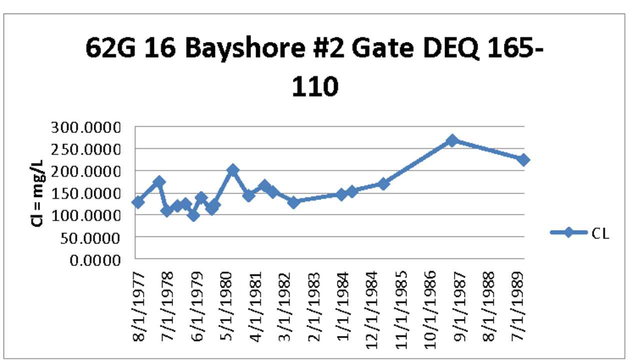

56H 25 Diascund SOW 177A DEQ 147-169
Cl = mg/L
500.0000
400.0000
300.0000
200.0000
100.0000
0.0000
10/10/1984
10/10/1986
10/10/1988
10/10/1990
10/10/1992
10/10/1994
10/10/1996
10/10/1998
10/10/2000
10/10/2002
10/10/2004
CL

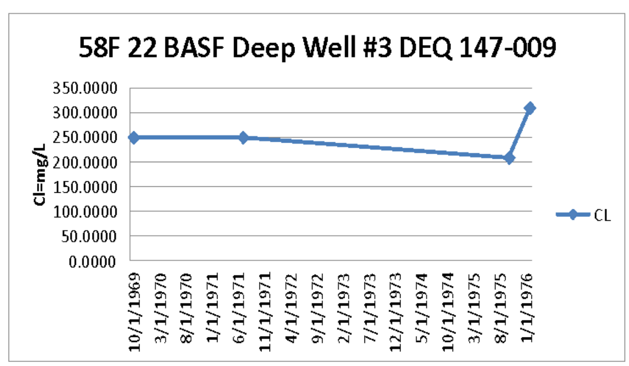

59C 47 City of Chesapeake Western Branch MW-1 DEQ 234-210
Cl = mg/L
300.0000
250.0000
200.0000
150.0000
100.0000
50.0000
0.0000
4/1/2004
6/1/2004
8/1/2004
10/1/2004
12/1/2004
2/1/2005
4/1/2005
6/1/2005
8/1/2005
10/1/2005
12/1/2005
2/1/2006
4/1/2006
6/1/2006
8/1/2006
CL

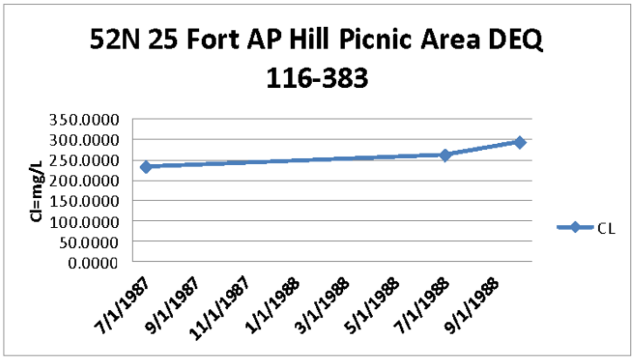

60C 35 Portsmouth Plant North WE-3 DEQ 220-003
Cl = mg/L
500.0000
400.0000
300.0000
200.0000
100.0000
0.0000
7/19/1974
7/19/1975
7/19/1976
7/19/1977
7/19/1978
7/19/1979
7/19/1980
7/19/1981
7/19/1982
7/19/1983
7/19/1984
7/19/1985
7/19/1986
7/19/1987
7/19/1988
CL

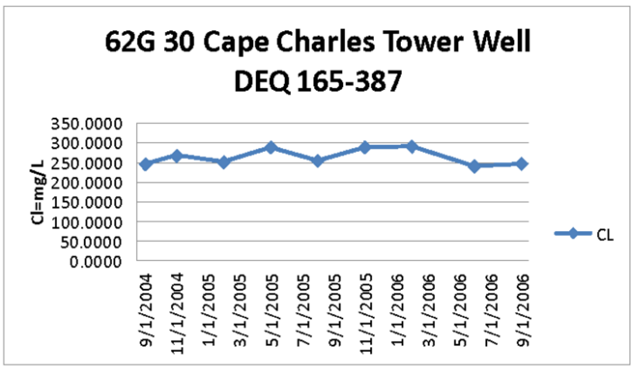

60C 7 Portsmouth PP Sewage Disposal DEQ 220-004
Cl = mg/L
400.0000
300.0000
200.0000
100.0000
0.0000
6/1/1969
9/1/1971
12/1/1973
3/1/1976
6/1/1978
9/1/1980
12/1/1982
3/1/1985
6/1/1987
9/1/1989
12/1/1991
3/1/1994
6/1/1996
9/1/1998
12/1/2000
3/1/2003
CL

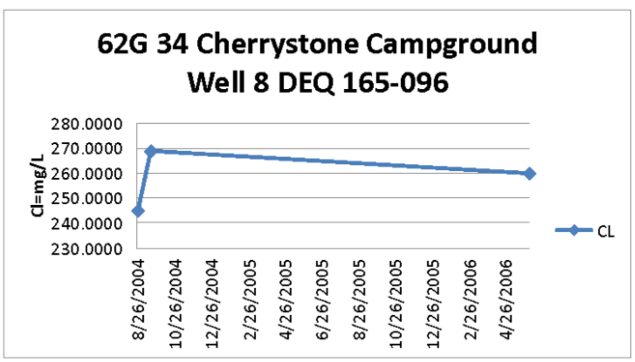

56F 56 James City Service Authority BGD-2 DEQ 147-294
Cl=mg/L
400.0000
300.0000
200.0000
100.0000
0.0000
3/1/2002
7/1/2002
11/1/2002
3/1/2003
7/1/2003
11/1/2003
3/1/2004
7/1/2004
11/1/2004
3/1/2005
7/1/2005
11/1/2005
3/1/2006
7/1/2006
CL


62G 16 Bayshore #2 Gate DEQ 165-110
Cl =mg/L
300.0000
250.0000
200.0000
150.0000
100.0000
50.0000
0.0000
8/1/1977
7/1/1978
6/1/1979
5/1/1980
4/1/1981
3/1/1982
2/1/1983
1/1/1984
12/1/1984
11/1/1985
10/1/1986
9/1/1987
8/1/1988
7/1/1989
CL

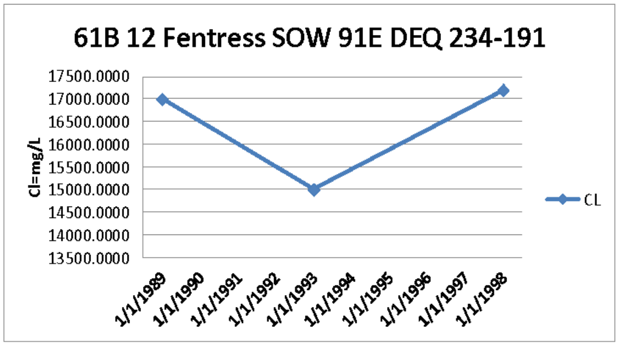

58F 22 BASF Deep Well #3 DEQ 147-009
Cl=mg/L
350.0000
300.0000
250.0000
200.0000
150.0000
100.0000
50.0000
0.0000
10/1/1969
3/1/1970
8/1/1970
1/1/1971
6/1/1971
11/1/1971
4/1/1972
9/1/1972
2/1/1973
7/1/1973
12/1/1973
5/1/1974
10/1/1974
3/1/1975
8/1/1975
1/1/1976
CL

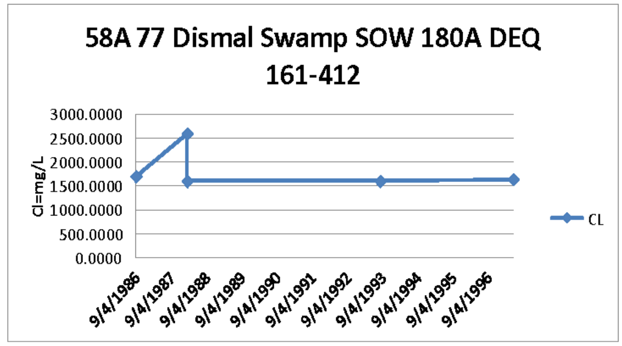

52N 25 Fort AP Hill Picnic Area DEQ 116-383
350.0000
300.0000
250.0000
200.0000
150.0000
100.0000
50.0000
0.0000
Cl=mg/L
7/1/1987
9/1/1987
11/1/1987
1/1/1988
3/1/1988
5/1/1988
7/1/1988
9/1/1988
CL

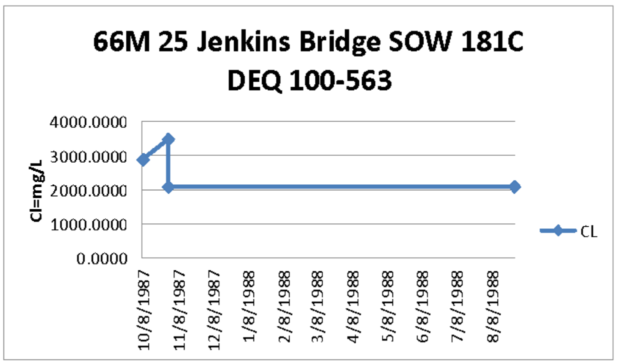

62G 30 Cape Charles Tower Well DEQ 165-387
350.0000
300.0000
250.0000
200.0000
150.0000
100.0000
50.0000
0.0000
Cl=mg/L
9/1/2004
11/1/2004
1/1/2005
3/1/2005
5/1/2005
7/1/2005
9/1/2005
11/1/2005
1/1/2006
3/1/2006
5/1/2006
7/1/2006
9/1/2006
CL

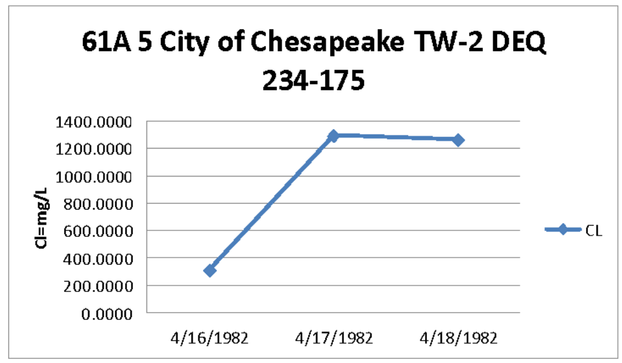

62G 34 Cherrystone Campground Well 8 DEQ 165-096
280.0000
270.0000
260.0000
250.0000
240.0000
230.0000
Cl=mg/L
8/26/2004
10/26/2004
12/26/2004
2/26/2005
4/26/2005
6/26/2005
8/26/2005
10/26/2005
12/26/2005
2/26/2006
4/26/2006
CL

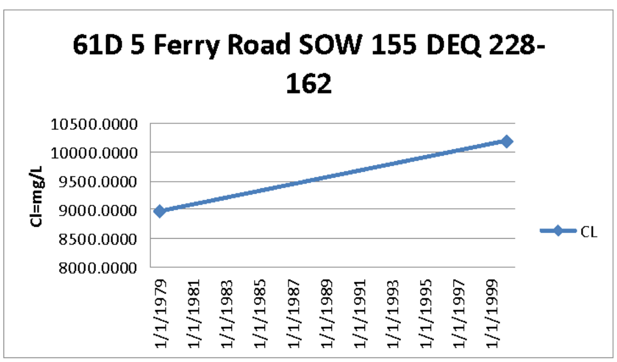
Proposed Tier 2 Wells Chloride Data Plots

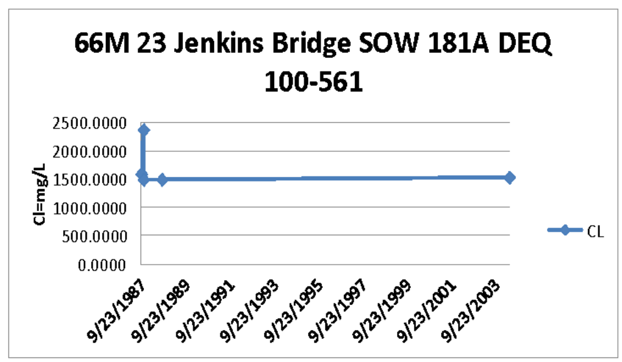

61B 12 Fentress SOW 91E DEQ 234-191
Cl=mg/L
CL

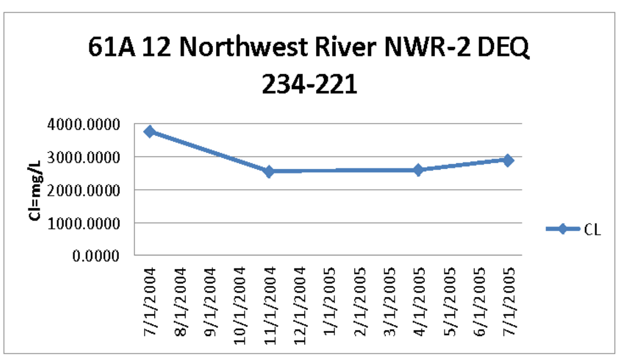

58A 77 Dismal Swamp SOW 180A DEQ 161-412
Cl=mg/L
CL

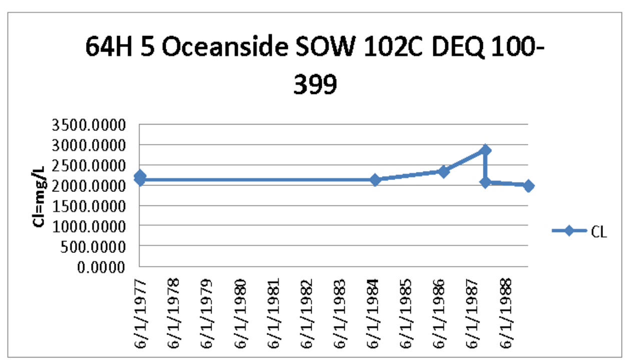

66M 25 Jenkins Bridge SOW 181C DEQ 100-563
Cl=mg/L
CL

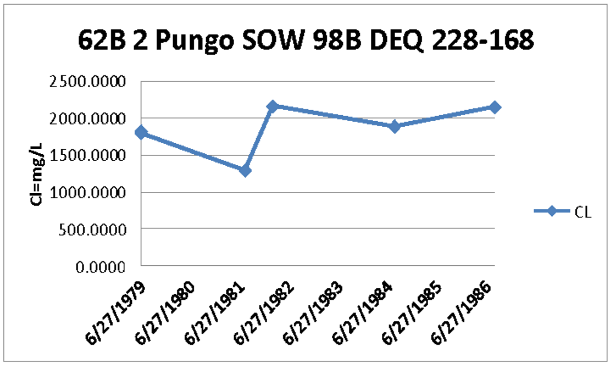

61A 5 City of Chesapeake TW-2 DEQ 234-175
Cl=mg/L
CL

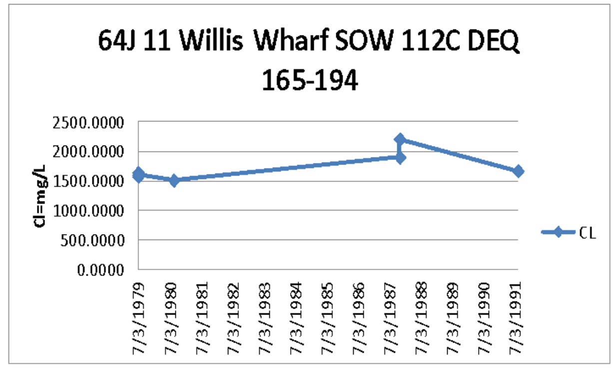

61D 5 Ferry Road SOW 155 DEQ 228-162
Cl=mg/L
CL

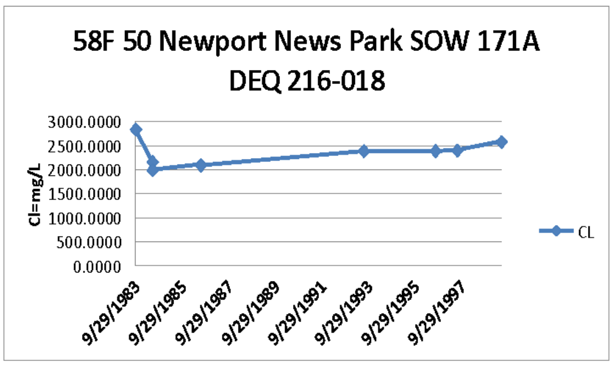

66M 23 Jenkins Bridge SOW 181A DEQ 100-561
Cl=mg/L
CL

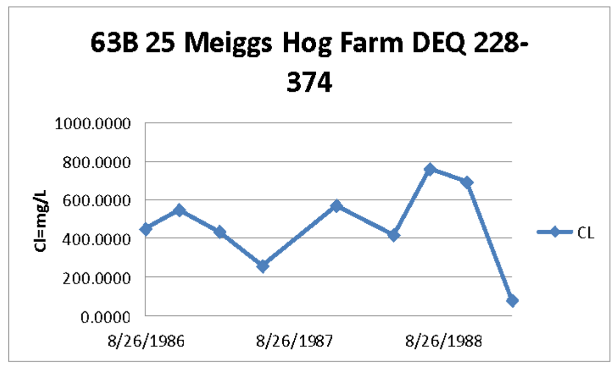

61A 12 Northwest River NWR-2 DEQ 234-221
Cl=mg/L
CL

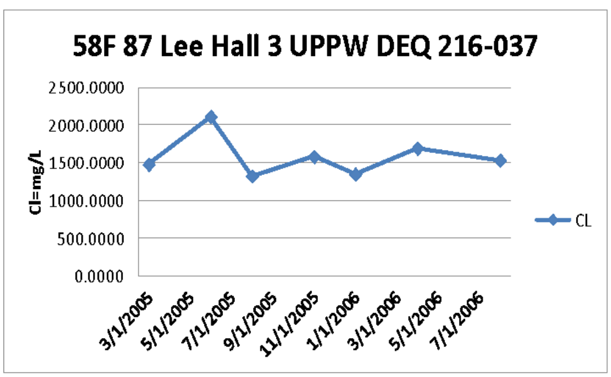

64H 5 Oceanside SOW 102C DEQ 100-399
Cl=mg/L
CL

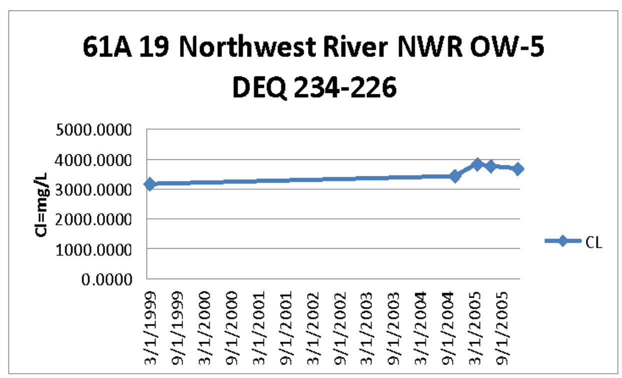

62B 2 Pungo SOW 98B DEQ 228-168
2500.0000
2000.0000
1500.0000
1000.0000
500.0000
0.0000
Cl=mg/L
6/27/1979
6/27/1980
6/27/1981
6/27/1982
6/27/1983
6/27/1984
6/27/1985
6/27/1986
CL

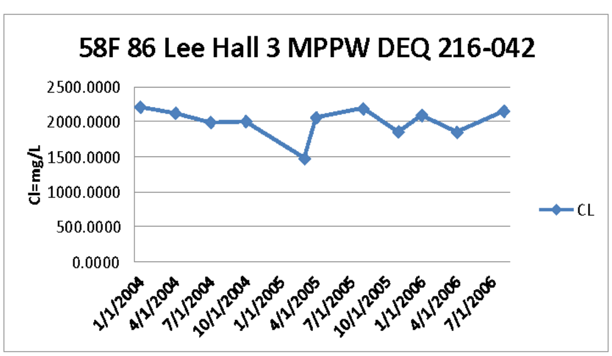

64J 11 Willis Wharf SOW 112C DEQ 165-194
2500.0000
2000.0000
1500.0000
1000.0000
500.0000
0.0000
Cl=mg/L
7/3/1979
7/3/1980
7/3/1981
7/3/1982
7/3/1983
7/3/1984
7/3/1985
7/3/1986
7/3/1987
7/3/1988
7/3/1989
7/3/1990
7/3/1991
CL

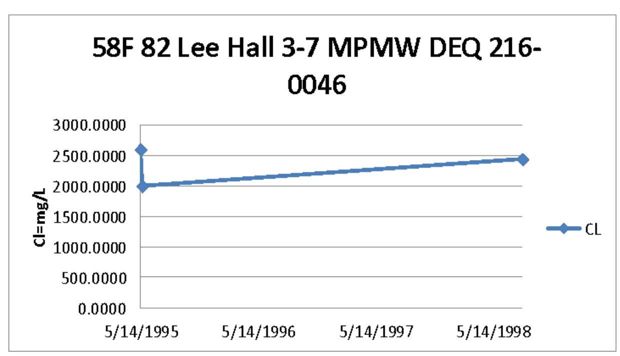

58F 50 Newport News Park SOW 171A DEQ 216-018
3000.0000
2500.0000
2000.0000
1500.0000
1000.0000
500.0000
0.0000
Cl=mg/L
9/29/1983
9/29/1985
9/29/1987
9/29/1989
9/29/1991
9/29/1993
9/29/1995
9/29/1997
CL

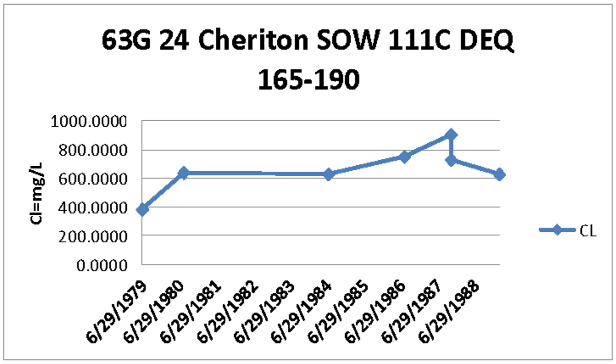

63B 25 Meiggs Hog Farm DEQ 228-374
1000.0000
800.0000
600.0000
400.0000
200.0000
0.0000
Cl=mg/L
8/26/1986
8/26/1987
8/26/1988
CL

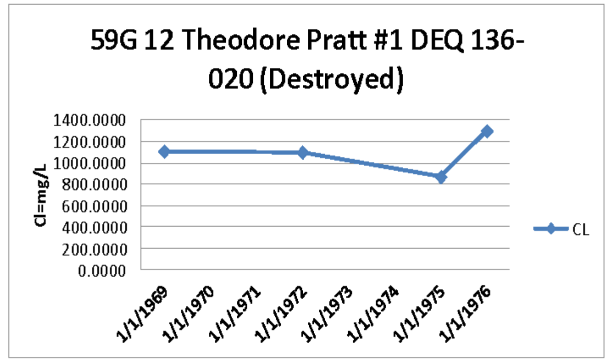

58F 87 Lee Hall 3 UPPW DEQ 216-037
2500.0000
2000.0000
1500.0000
1000.0000
500.0000
0.0000
Cl=mg/L
3/1/2005
5/1/2005
7/1/2005
9/1/2005
11/1/2005
1/1/2006
3/1/2006
5/1/2006
7/1/2006
CL

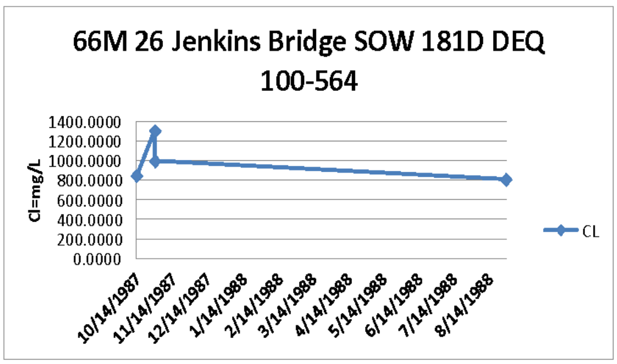

61A 19 Northwest River NWR OW-5 DEQ 234-226
5000.0000
4000.0000
3000.0000
2000.0000
1000.0000
0.0000
Cl=mg/L
3/1/1999
9/1/1999
3/1/2000
9/1/2000
3/1/2001
9/1/2001
3/1/2002
9/1/2002
3/1/2003
9/1/2003
3/1/2004
9/1/2004
3/1/2005
9/1/2005
CL

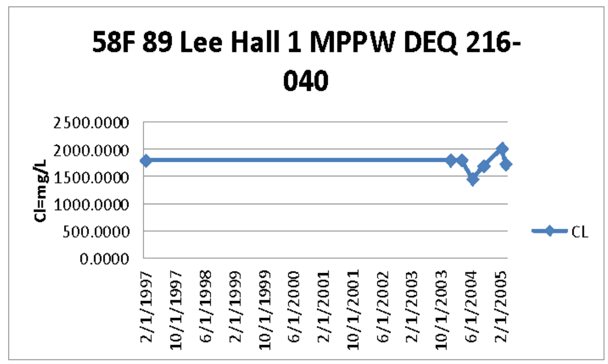

58F 86 Lee Hall 3 MPPW DEQ 216-042
2500.0000
2000.0000
1500.0000
1000.0000
500.0000
0.0000
Cl=mg/L
1/1/2004
4/1/2004
7/1/2004
10/1/2004
1/1/2005
4/1/2005
7/1/2005
10/1/2005
1/1/2006
4/1/2006
7/1/2006
CL

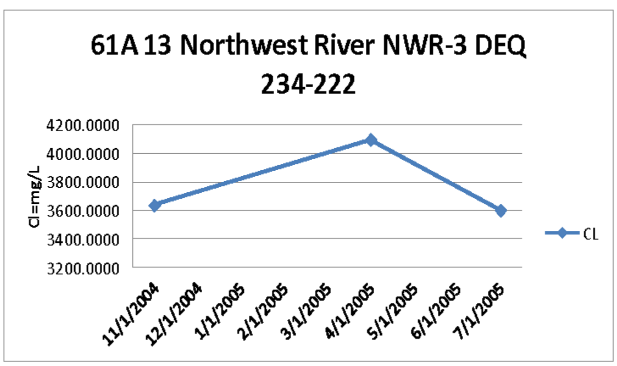

58F 82 Lee Hall 3-7 MPMW DEQ 216-0046
3000.0000
2500.0000
2000.0000
1500.0000
1000.0000
500.0000
0.0000
Cl=mg/L
5/14/1995
5/14/1996
5/14/1997
5/14/1998
CL

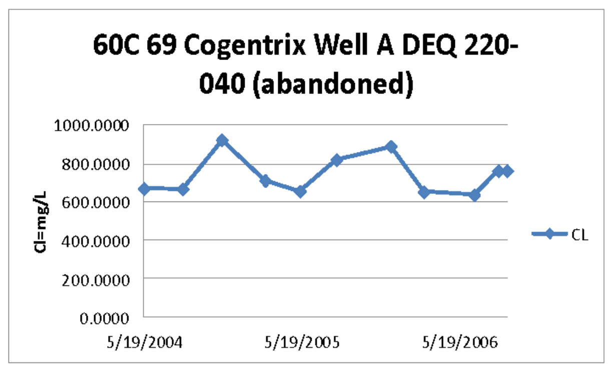

63G 24 Cheriton SOW 111C DEQ 165-190
Cl=mg/L
1000.0000
800.0000
600.0000
400.0000
200.0000
0.0000
6/29/1979
6/29/1980
6/29/1981
6/29/1982
6/29/1983
6/29/1984
6/29/1985
6/29/1986
6/29/1987
6/29/1988
CL

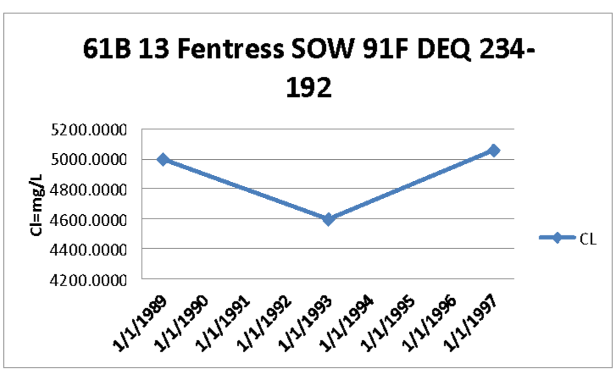

59G 12 Theodore Pratt #1 DEQ 136-020 (Destroyed)
Cl=mg/L
1400.0000
1200.0000
1000.0000
800.0000
600.0000
400.0000
200.0000
0.0000
1/1/1969
1/1/1970
1/1/1971
1/1/1972
1/1/1973
1/1/1974
1/1/1975
1/1/1976
CL

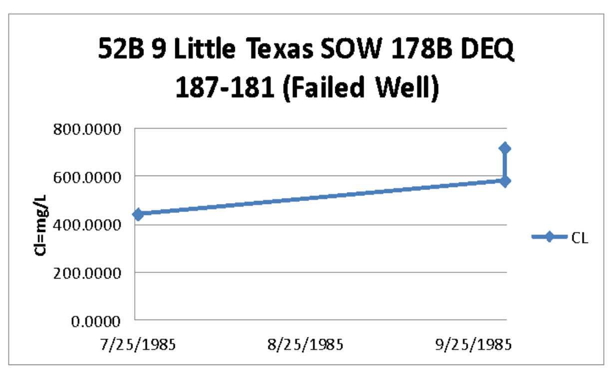

66M 26 Jenkins Bridge SOW 181D DEQ 100-564
Cl=mg/L
1400.0000
1200.0000
1000.0000
800.0000
600.0000
400.0000
200.0000
0.0000
10/14/1987
11/14/1987
12/14/1987
1/14/1988
2/14/1988
3/14/1988
4/14/1988
5/14/1988
6/14/1988
7/14/1988
8/14/1988
CL


58F 89 Lee Hall 1 MPPW DEQ 216-040
Cl=mg/L
2500.0000
2000.0000
1500.0000
1000.0000
500.0000
0.0000
2/1/1997
10/1/1997
6/1/1998
2/1/1999
10/1/1999
6/1/2000
2/1/2001
10/1/2001
6/1/2002
2/1/2003
10/1/2003
6/1/2004
2/1/2005
CL


61A 13 Northwest River NWR-3 DEQ 234-222
Cl=mg/L
4200.0000
4000.0000
3800.0000
3600.0000
3400.0000
3200.0000
11/1/2004
12/1/2004
1/1/2005
2/1/2005
3/1/2005
4/1/2005
5/1/2005
6/1/2005
7/1/2005
CL


60C 69 Cogentrix Well A DEQ 220-040 (abandoned)
Cl=mg/L
1000.0000
800.0000
600.0000
400.0000
200.0000
0.0000
5/19/2004
5/19/2005
5/19/2006
CL


61B 13 Fentress SOW 91F DEQ 234-192
Cl=mg/L
5200.0000
5000.0000
4800.0000
4600.0000
4400.0000
4200.0000
1/1/1989
1/1/1990
1/1/1991
1/1/1992
1/1/1993
1/1/1994
1/1/1995
1/1/1996
1/1/1997
CL


52B 9 Little Texas SOW 178B DEQ 187-181 (Failed Well)
Cl=mg/L
800.0000
600.0000
400.0000
200.0000
0.0000
7/25/1985
8/25/1985
9/25/1985
CL